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AN ANALYSIS OF THE CENTER OF GRAVITY OF THE ARM DURING CERTAIN SIMULATED INDUSTRIAL MOVEMENTS

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CHAPTER I

INTRODUCTION

The purpose of this study is to investigate the center of gravity of the total arm complex during certain work movements typical of those in use in industrial tasks. The center of gravity characteristics investigated are the distance and path traveled and the nature and behavior of the velocity of the center of gravity during that travel. The results of this study can be used to further the available knowledge of applying classical mechanical laws to the human body in motion.

History

Man has attempted for many years to relate the laws of mechanics to human motion. Because of the complicated and, at the present, rather vague knowledge of the application of forces of the body muscles, there is no exact mathematical method of accomplishing the complete application of mechanical forces to human work when considering all locomotor factors. However, in such locomotion events as walking and movement of the arm complex, Newton's laws of motion are definitely in use and these locomotor events can be analyzed by use of the laws of mechanics [1, 3].

The application of mechanical laws to the case of body motion provides an interesting area of study. The application to date has been limited to determining the center of gravity of the total body and the center of gravity of the body segments. The knowledge of the locations of the centers of gravity has found some application in the area of design and development of artificial limbs for the body. The physical therapists have utilized the available data in studying the forces that should be placed on the injured or deformed human limbs. The engineer's application of the laws of mechanics to human body seems to be concentrated on the location of the center of gravity. Very little practical use of this knowledge has been presented. All experiments on the location of the center of gravity have yielded remarkably close results and this area seems to be adequately explored.

Of primary interest to the industrial engineer is the subject of fatigue and physiological costs to the human body while performing an industrial task. By developing procedures which include the application of mechanical laws to the human body in motion, a new and hopefully improved and more accurate method of measuring energy expenditure might be developed. The possibility of a new method to measure human work certainly demands that the industrial engineer investigate the application of the laws of mechanics to the human body in motion.

The study of the center of gravity of the body in motion and, consequently, the center of gravity of the body segments in motion falls within the field of knowledge called kinesiology. The word kinesiology is derived from the word kineo, which means I-move. As the meaning implies, kinesiology is the study of human motion. Kinesiology can further be defined as [1] that part of physiology of motion which describes and analyzes human locomotor events as they reflect the action of mechanical forces. Within the field of kinesiology the specific area of reference is called biomechanics. Since biomechanics is a study of humans, it draws upon the fields of anatomy and pathology. Since biomechanics relates human movements to mechanical actions, it must necessarily draw on the established laws of mechanics.

The earliest work in biomechanics [1] can be traced back to ancient Greece. Hippocrates (460 B.C.) and Aristotle (334 B.C.) both applied mechanical views and geometrical analysis to body locomotion. Claudius Galen (131-201 A.D.) was the first to bring forth physiological facts as we use them today in connection with kinesiology. Borelli (1608-1679) made notable contributions to human mechanics. Borelli reported his balance board experiment in 1680 [4] and became the first investigator to report on the location of the traverse plane of gravity. With this simple experiment Borelli became the father of

biomechanics. Other contributors to the early knowledge of the field were: Nicolas Stevo (1632-1686), Georgio Baglivi (1668-1707), Lieuwenback (1715), and J. Keill (1708).

The modern era of biomechanics began with the work of [4] Edward Weber (1806-1871) and Henrick Weber (1795-1878). The Webers in 1836 did the first quantitative work on the problem of the center of gravity of the body. They were able to report for two subjects both the absolute height of the traverse plane above the soles, and its relative height, expressed as a percentage of body length or stature.

Harless (1860) provided the first experimentation data on finding the mass and center of gravity of the various segments of the body. He dismembered two young adult cadavers [5], weighed the various segments, measured segment lengths, and the relative distances from the center of gravity to the segment extremities were determined.

The next notable work came from Braune and Fisher, two of the greatest kinesiologists of the latter half of the nineteenth century [4, 5, 6]. Braune and Fisher froze three cadavers in the supine position and the limb joints were sawed across at planes which were presumed to transect joint centers. They then determined the mass and center of gravity of the segments. The data that they

found on body mass are considered classical and they are used to this day. Another important contribution [5, 6] from the same experiment was the discovery that with slight adjustment the various joint centers and the various centers of gravity could be aligned in a horizontal plane relative to the supine body. Braune and Fisher reasoned that this position approximated a living subject in normal standing posture. By considering the joint centers and the centers of gravity in the Y-Z plane, they used the principle of summing moments of force about a fixed point to calculate the center of gravity of the whole body. The results were well within the limits of measurement error on the specimen from which the segment parts were obtained. Braune and Fisher thus provided the first experimental results which definitely supported the application of the laws of mechanics to the field of kinesiology.

In the years following Braune and Fisher's work, numerous experiments were conducted on determining the center of gravity of the total body, segment mass, moment of inertia, and the specific gravity of the human body. However, the majority of the experiments were orientated toward improving the knowledge of the use and construction of artificial limbs. World War I had the effect of increasing interest in artifical limbs and overshadowing the investigation of applying mechanical laws to human

motion for the purpose of improving industrial work methods and machine design. The industrial engineer's approach to measuring energy expenditure took the form of the calorimetric techniques, and this procedure is used to the present date. Perhaps the inherent difficulty in changing from established procedures to new techniques has contributed to the void in practical application of mechanical laws to the human body while performing industrial tasks.

Arthur Steindler [1, 2] in 1935 presented a comprehensive work relating to the mechanics of human locomotion. Steindler presented a brief review of the past work and contributed data of his own. However, no application of the data was presented. From the literature available there is little recorded progress made in the area of the center of gravity of the human body until Dempster [5]. This is not to be interpreted to mean that no valuable information was presented in the general area of kinesiology. Many worth-while studies were undertaken, especially in relation to human limbs and their substitutes. However, Dempster's work was by far the most thorough and comprehensive conducted in recent years.

Dempster in his work on the requirements of the seated operator [5] conducted tests on eight male cadavers. He stated in his report:

> In our approach it has been assumed that the primary current use of body constants would be in the analysis of a variety of problems in body mechanics involving specific test subjects. It was also assumed that if satisfactory data on body constants were available, static postures or instantaneous phases of body movement could be analyzed mechanically from photographic records, including possibly, simultaneous records in different planes of space. Probably in many instances static or dynamic data on whole body reaction forces would also be available for analyses of posture and movement. To this end, Braune and Fisher coordinate system seemed less important than basic data on segment masses, on centers of gravity of parts relative to joint centers and on moments of inertia of the body members. The data derived from our procedures accordingly, were concerned with segments per se, rather than with whole body systems. [5]

With the purpose of obtaining standard data for use in body mechanics problems with live subjects, Dempster obtained the following information: measurements of segment mass, segment volume, position of center of gravity relative to length, the moment of inertia, and the anatomical location of the center of gravity, which enabled him to determine the location of the position of the center of gravity in the cross sectional area. Dempster presents his data in tabular form in his report.

The three-dimensional data obtained by Dempster showed that the centers of gravity of the limb segments, except for the shoulders, were characteristically aligned between the joint centers. He concluded that since centers of gravity tend to be aligned between adjacent joint centers, data for more or less general use on the location of the centers of gravity of the limb segments may be

based simply on the relative distance of the center to adjacent proximal and distal joint centers. He provides a table with the location of the segment centers as a percentage of distance from the proximal and distal ends of the segments. Dempster's data on the distance of the center of gravity from the adjacent proximal and distal joint centers are shown in Appendix A.

The locations of the centers of gravity of the segments in the eight cadavers were remarkably constant when considered in terms of percentage distance from the proximal to distal axes of rotation. Deviations of the locations in the segments were found to be less than one per cent.

A brief discussion of the concept of body links is now necessary. In kinematic analysis of human motion, the important moving units are not the various bones [3] but the total mass of the segments which turn about the joint axis. The rotational axes are not located at the junctions of the bones. For instance, at the shoulder it is within the humeral head. These points are called joint centers. The central straight line, which extends between two joint centers, is termed a "link." The center of gravity of a segment lies on the link between the respective joint centers. The body surface landmarks associated with the joint centers that Dempster used to measure the link dimensions are shown in Appendix B.

Dempster also determined the weight of the various segments as a percentage of the total weight. His subject was a one hundred fifty (150) pound male of relatively good build. He presents the results of this experiment in tabular form [5] listing the hand as .6% of total weight, forearm 1.6%, and the arm as 2.7%. He then compared these figures with data from live subjects, and the results were extremely close. The data found by Dempster on the segment weight as a percentage of total weight are shown in Appendix C.

Dempster's comprehensive work has provided standard data that can be utilized in the general analysis of human body members. He does not apply his data of the segmental centers of gravity to any problems in the area of human motion. After a thorough search in the available material, only one application of this valuable data has been found. Williams and Lissner [3] used the data in problems relating to physical therapy. They used the principle of resolving moments about a point to determine the resultant force on limbs. They also present a method of finding the resultant center of gravity of two or more body segments. This method is based on the principle of resolving moments about a point and is presented in only one plane. Their problems deal strictly with a stationary limb, and they make no application to a moving body member.

The greatest application of the data developed by Braune, Fisher, and Dempster has centered on man's effort to enter space. Several studies sponsored by various government agencies have related to the centers of gravity of the human in different body positions. The following references relate to studies sponsored by government agencies. These have been taken from the work of Hanavan [13], which was the only reference available. Although a review of these studies was not possible, they should be referenced since they deal with the center of gravity of the body. Hanavan briefly reviewed the studies, and from his discussion it is concluded that the research was directed toward space problems and not industrial problems. Barter [9] used the data to derive a set of regression equations for the weight of the body sections. Swearingen [10] determined the centers of gravity of living subjects in sixty-seven different body positions. King [11] investigated the locus of the center of gravity for a variety of body positions. Santschi, DuBois, and Omoto [12] determined the center of gravity and moments of inertia of sixty-six living subjects in eight body positions. Hanavan [13] used data on the center of gravity to develop a mathematical model of the human body. All of these studies were orientated toward the weight and weightless problems that man encounters when in the environment of space. The value of Dempster's standard data

for exploring the physiological cost to a human performing industrial tasks seems to be relatively unused at the present time.

The importance of research in the kinematic analysis of body movement was well stated by C. L. Taylor and A. C. Blaschke:

> A workable method for Kinematic Analysis should not long await application to many fields of human biology. It opens the way to dynamic analysis of all types of manual work. The calorimetric techniques for measurement of the energy in such work have long been recognized to lack the specificity and sensitivity necessary for a scientific formulation of the vast array of light activity types. They fail to differentiate clearly the work done in moving the body structures from that done against external loads. Hence, it is expected that the physical analysis of biomechanics will contribute in a very fundamental way to the investigation of human energetics in manual work. [7]

The data made available by Dempster need to be applied to the body in motion to be of value in determining energy expenditure. Dr. E. R. Tichauer [8] in an unpublished article in the Industrial Engineering Department at Texas Technological College provides information on the travel of the center of gravity of the arm complex when transporting two different external loads. However, a review of the available literature has shown that relatively little progress has been made in using available data in useful research in this area. The present research deals with the travel of the center of gravity of the arm complex in simulated industrial movements.

Purpose and Scope

The primary purpose of this investigation is to determine the distance and path traveled by the center of gravity of the total arm complex during certain work movements typical of those used in industrial tasks and to analyze the behavior of the velocity of the center of gravity during each of the movements. A comparison between the results for each move will be made for the purpose of determining differences that may or may not exist between each movement. The comparison of the results of each move should yield certain conclusions relating to what effect the center of gravity has in performing the simulated task.

The experiment was designed so that all moves considered were within the normal work area of a seated worker as proposed by Barnes [14]. All moves were straight line motion and remained in the horizontal plane. The performance of the subjects was controlled by using a metronome to pace all movements. Subjects were chosen from graduate students of industrial engineering and were limited to right-handed males. All experimentation was with moves by the right hand. The criterion for determining the total distance and path traveled by the center of gravity was the rectangular coordinates of the center of gravity at the end points and each two-inch increment of the move. The center of gravity was assumed to travel in

a straight line between adjacent coordinates. This assumption is valid since a curve can be approximated by small straight line increments. The time for the total move and the time between increments of move were recorded. Thus, knowing the distance traveled and the time of travel, the velocity of the center of gravity was calculated.

It is hoped that this investigation will contribute some preliminary information in the area of measuring the physiological cost to the worker in performing industrial tasks. The apparatus used as well as the procedure for experimentation is discussed in the following chapters.

CHAPTER II

DESIGN AND USE OF THE EQUIPMENT

Design

The equipment was designed to provide a simulated work place typical of one that might be used for a seated production worker. Mechanical and electrical devices for recording arm movement times in two-inch increments were mounted on a table before the worker. The table served as a work bench for the other equipment and insured that all work was conducted in a horizontal plane. An adjustable industrial type chair with a back rest was used to make the table height accommodate any of the three subjects used.

Reference point A was located on the intersection of the work place surface and the midsagittal plane of the seated worker and 6 inches inside the forward edge of the table and 33 inches inside the right side of the table. This reference point served as the starting point for each move. (See Figure 1.)

The electrical path board was placed on the work table in such a manner that the center of the prescribed path on the board and the first electrical contact were directly centered over reference point A. (See Figure 2.)

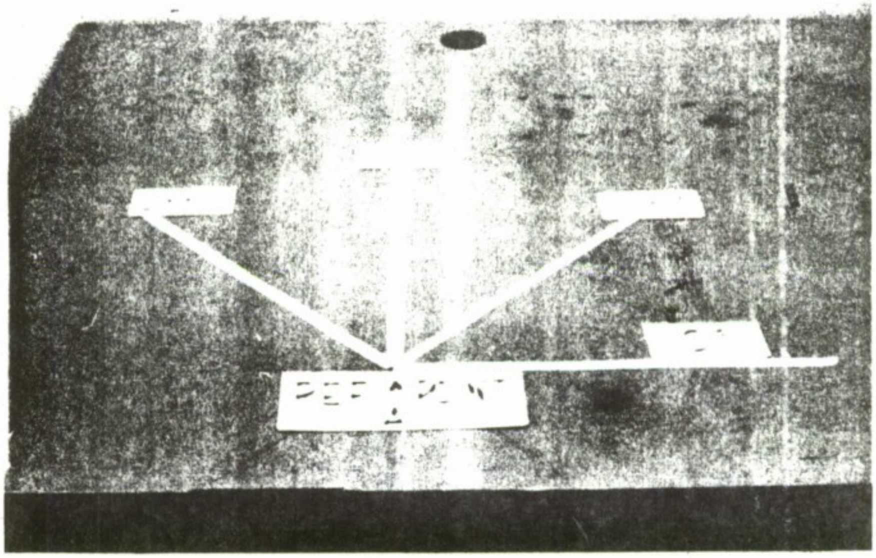

Fig. 1.--Reference point A

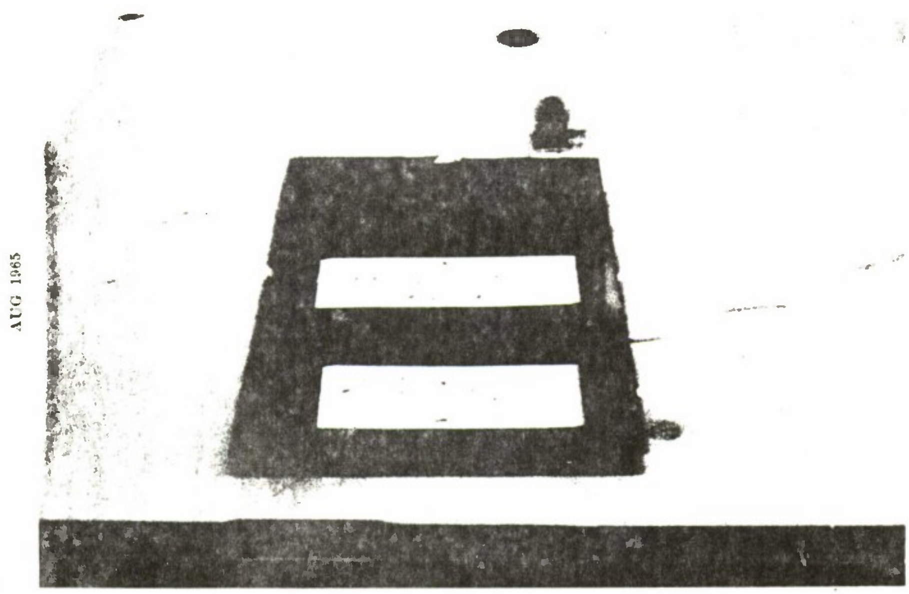

Fig. 2.--Electrical path board positioned over reference point A.

The bottom of the board was equipped with a swivel contact at this point so the board would rotate freely about reference point A. The board could then be rotated through any angle from 0 to 180 degrees. The angles used in this experiment were 0, 45, 90, and 135 degrees in reference to point A and the frontal plane of the subject. All moves were within the normal work area of a seated worker as proposed by Barnes [14]. The electrical path board is a board one-half inch high, fourteen inches wide, and seventeen inches long. The board is equipped with electrical contacts in two-inch intervals over a twelve-inch span for a total of seven contacts. The first contact is at a point four inches from the bottom of the board, and the last contact is one inch from the top of the board. (See Figure 3.) The first contact was placed four inches from the bottom of the board to allow the subject room to place his hand on the board after grasping the stylus. A small light bulb was mounted on the top of the board and was wired into the circuit. When the stylus touched any of the seven contacts, this light would come on, showing exactly when the stylus touched the contact. This aided in measuring the spherical coordinates.

The electrical contacts of the board were wired so that it could be used with the OFFNER Type R dynograph. A wiring diagram of the electrical path board is shown in Figure 4. The dynograph will register when the stylus

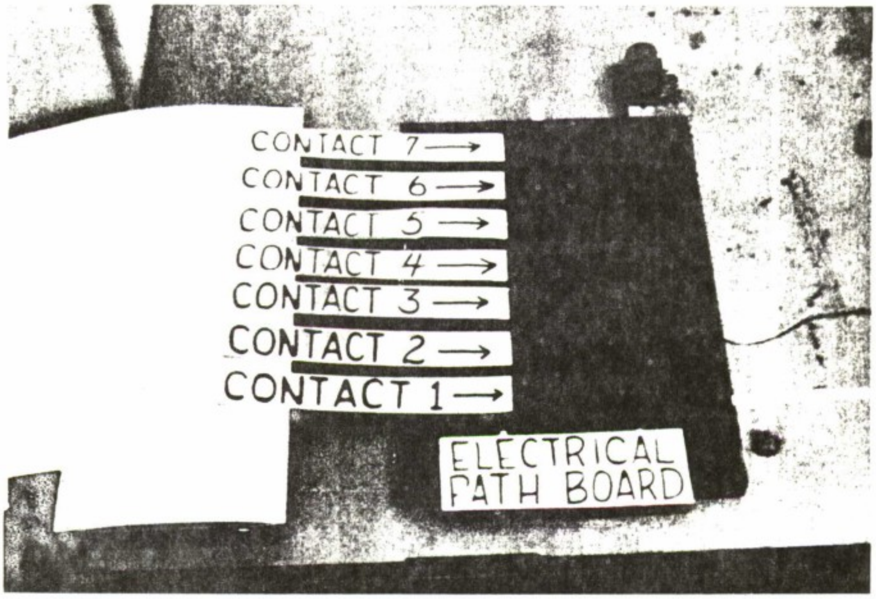

Fig. 3.--Electrical path board without prescribed path cover

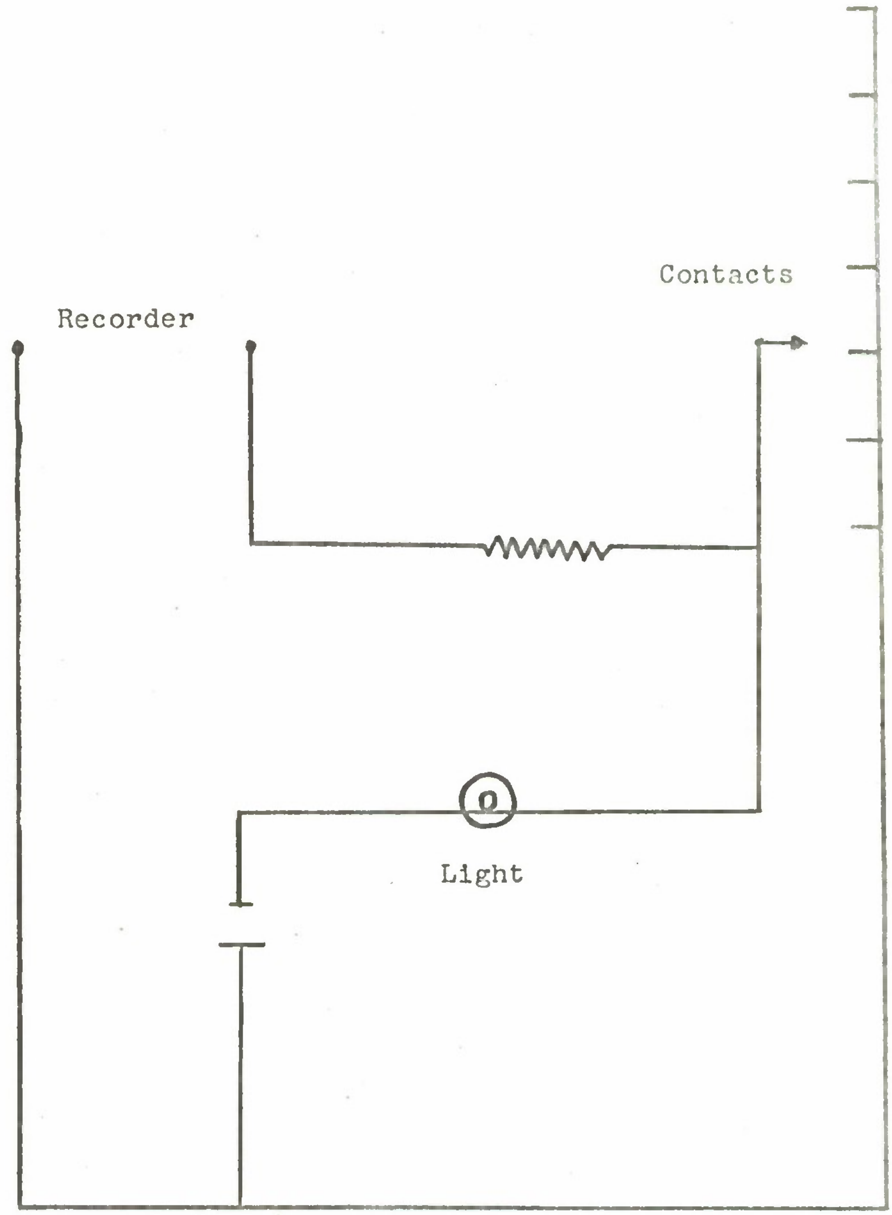

Fig. 4.--Wiring diagram for the electrical path board

passes over the contacts on the electrical path board. Since the speed of the paper on the dynograph can be set at a desired and constant rate, the time between contacts can be determined by using the knowledge of the speed of the paper and physically reading the length of the paper between the register marks. The sum of the increment times between contacts will equal the time for the total move.

The electrical path board was constructed so that a board with any desired predetermined path could be attached over the top as shown in Figure 2 (page 16). This predetermined path insured that all moves were identical. A straight line predetermined path was used for all movements in this experiment.

The metal tip of the stylus used in the experiment completed the circuit of the electrical path board when it was moved over the seven contacts. One stylus was used throughout the experiment. The stylus was designed to provide as little weight as possible for the subject to move. The weight was .2 pounds, and the length and diameter were 4.25 and 0.625 inches respectively. (See Figure 5.) To insure that each move was the same, a stylus guide was constructed. This guide slides along the prescribed path and the path was coated with silicon spray to reduce friction between the guide and the path. Two holes, one for the 135 and 90 degree moves and one for the 45 and 0

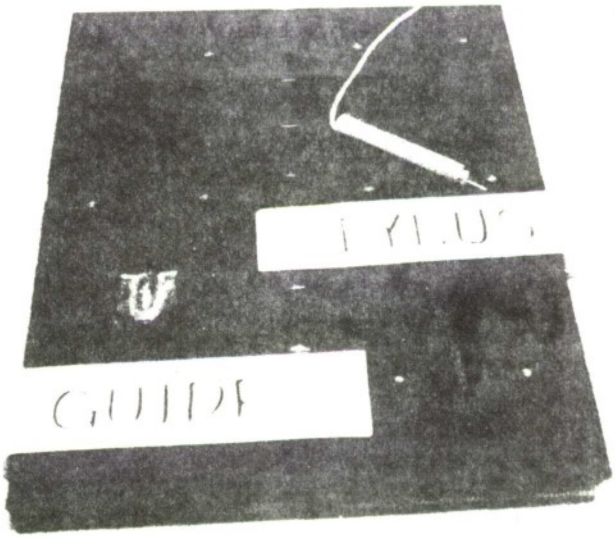

Fig. 5.--Stylus and stylus guide

degree moves, were drilled at an angle in the guide so the stylus would fit into the guide and protrude to the contact board below. Two different holes were necessary so that the subject could grasp the stylus in the same manner during each of the four directions. Since the stylus cannot be moved while in the guide, the hole used for the 90 and 135 degree moves would place the stylus in an awkward position for the 0 and 45 degree moves. To eliminate this problem, another hole was drilled in the stylus for the 0 and 45 degree moves. The subjects could then grasp the stylus, insert into the guide, and move from contact one to contact seven. (See Figure 6.) By combining the predetermined path board with the stylus guide it was insured that each repetition of a move traveled the exact same path. A metronome set at 76 beats per minute was used to pace all subjects while they were performing the task.

To measure the angle spherical coordinates of the arm segment's center of mass, an angle gauge was constructed. This angle gauge consisted of two protractors. Figure 7 shows how these protractors were mounted in reference to each other. The angle gauge served two purposes: (1) to measure the two angles, α and θ, necessary for spherical coordinate identification, and (2) the eyelets of the protractors served as the reference point for measuring the spherical coordinates. The angle gauge was mounted on top of a rotating steel rod which rotated

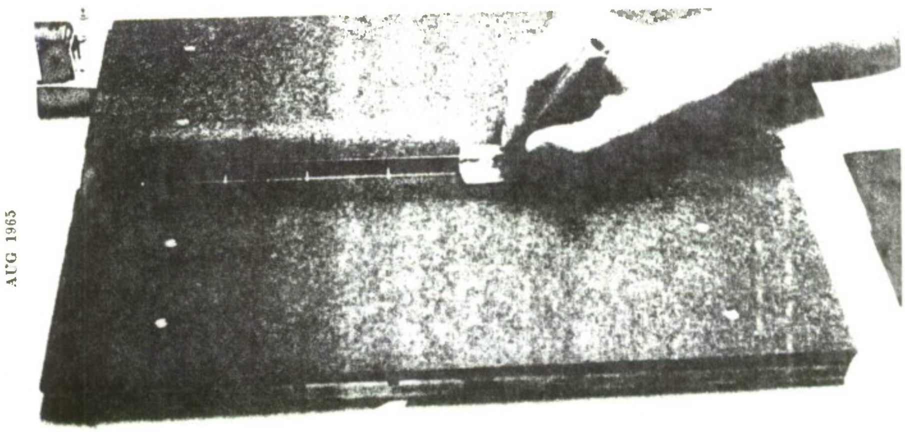

Fig. 6.--Subject moving stylus

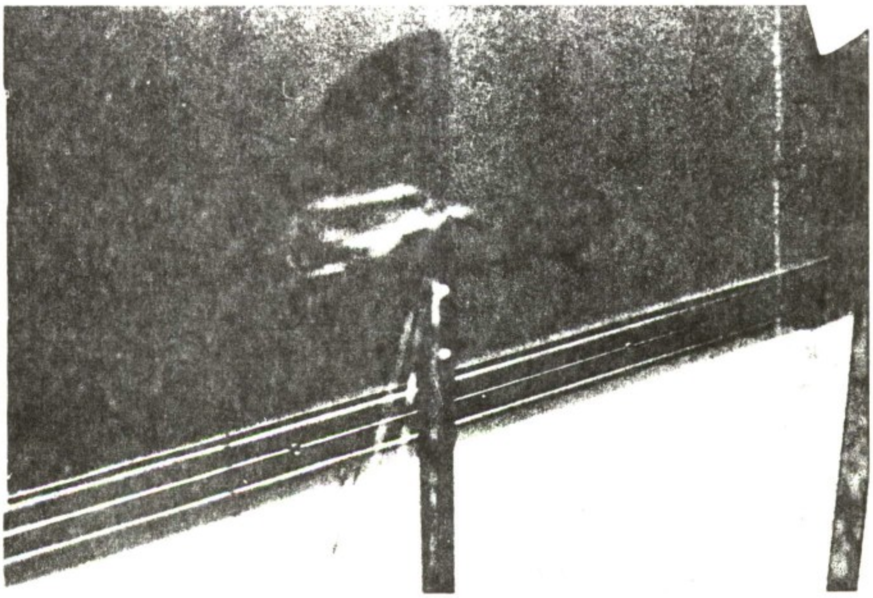

Fig. 7.--Angle gauge protractors

inside a cast iron pipe. The cast iron pipe was bolted to the table top by use of a floor flange. (See Figure 8.) The angle gauge was mounted on the right-hand side of the table top at a distance of 26-1/2 inches from the front edge. This location was chosen because all subjects were right-handed and it was desired to keep all coordinates in the same quadrant. At a point directly in front of the angle gauge a wooden dowel was attached to the table edge. The height of this dowel was 1/16 inch higher than the protractor parallel to the plane of the table top. A string was placed from the center of the top of the dowel across the 90 degree mark on the protractor and secured to the wall behind the angle gauge. Thus, when the angle gauge was rotated, the horizontal string served as a reference for reading the angle θ. To measure the radius necessary for spherical coordinates, three nylon strings were placed through the eyelet of the angle gauge. These strings were attached to leather straps which in turn were placed on the hand, forearm, and upper arm of the subject at points directly above the segment center of gravity. The straps were adjusted so that the point on the strap where the string was attached was directly above the center of gravity. (See Figure 9.) The distance from the angle gauge eyelet to the arm segment center of gravity could then be physically measured. The angle gauge could be rotated to the strings going to the hand, forearm,

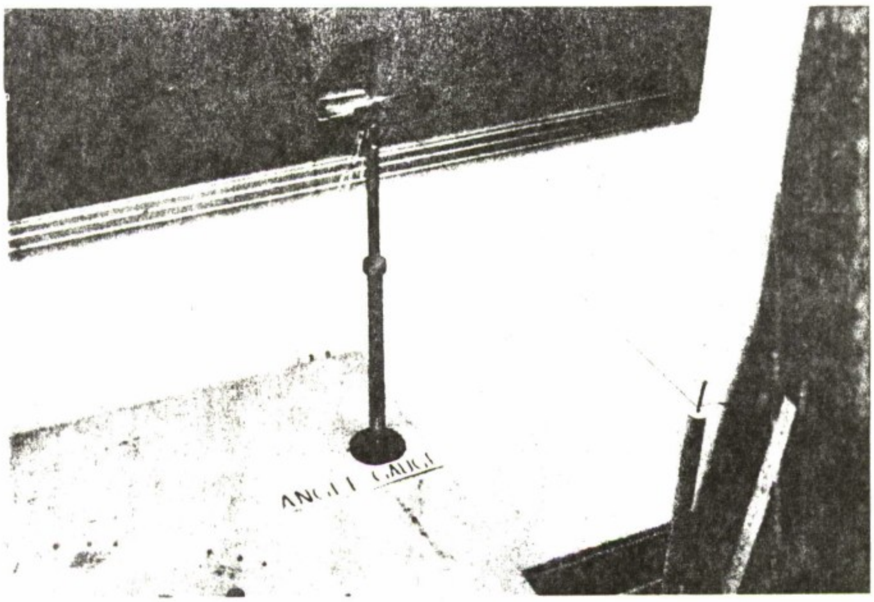

Fig. 8.--Angle gauge

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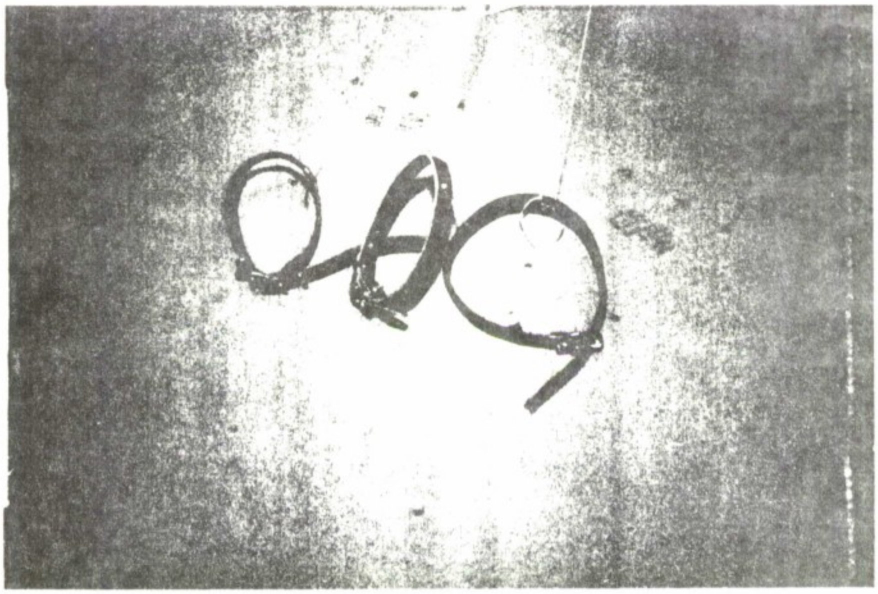


Fig. 9.--Radius strings and straps

and upper arm respectively, and the associated angle α read. A small lead weight was placed on the opposite end of each string to act as a balance. This weight pulled the strings backward through the eyelet thereby keeping the strings under tension at all times.

The height of the chair was adjusted for each subject, to provide a constant vertical height of one inch between the plane of the table top and the elbow when the arm was hanging naturally from the shoulder and the elbow was bent to approximately 90 degrees. The chair back support provided adequate back support and did not interfere with arm or shoulder movement required in the performance of the task. The subjects were required to sit in an erect position with back in contact with the chair. The chair was located to place the subject in a position where his hand would just move the stylus over the seventh contact with the board located in the 90 degree position. Figure 10 shows the subject properly seated and positioned for the beginning of a trial.

Use of Equipment

Before the experiment each subject performed for 15 minutes to 25 minutes to gain a complete understanding of the procedures and prevent any effect of practice.

Once a subject completed his familiarization, the first trial to obtain times for the moves was begun with

Fig. 10.--Subject seated at the apparatus

one of the four directions chosen at random. Table 1 shows the order in which the times were taken for each subject. Times were recorded for moves between contacts one and seven for the outward direction only. Ten repetitions were completed for each direction. This gave ten values for each increment and total time for all four directions of move. These values were averaged to obtain the value for each increment time and total time in each direction.

Beginning each move the subject would move the stylus to the first contact, then back off until the light on the electrical path board indicated that the stylus was directly adjacent to the first contact. The dynograph was then turned on and the subject would move to contact seven at the pace of the metronome. The dynograph was set at 100 mm per sec paper speed and as the stylus passed over a contact the dynograph registered on the paper. The distance of paper between register marks divided by the speed of the paper gave the time between contacts and consequently the total time for the move.

After the times were recorded, the spherical coordinates were then determined. The radii from the eyelet of the angle gauge were connected to the subject's hand, forearm, and upper arm at a point directly over the respective center of gravity. The subject would then move the stylus to the first contact. When the stylus touched the contact, the light mounted on the top of the

TABLE 1

ORDER OF TIME TRIALS

Subject	Direction
1	90°
	0°
	45°
	135°
2	90°
	135°
	0°
	45°
3	0°
	135°
	90°
	45°

electrical path board came on. Since the dynograph registered when the stylus first touched the contact, the light insured that the stylus was in the same place corresponding to the time trials. The angle gauge was then rotated to the radius going to the hand center of gravity. The angles α and θ were read directly from the protractors. The radius was marked in two-inch intervals so the intervals from the hand to the one closest to the angle gauge were counted; knowing the radius of the protractor, only the portion of the two-inch segment next to the protractor had to be measured. By adding the number of intervals, the radius of the protractor, and the measured length, the radius from the angle gauge eyelet to the point directly above the hand center of gravity was determined and recorded. The radius and the angles α and θ were then found for the forearm and upper arm in the same manner. The process was repeated at each of the seven contacts for all four movements. Each subject was required to run three trials for coordinate measurements. One trial is defined as the complete spherical coordinates for the hand, forearm, and upper arm centers of gravity at each contact, for any of the four movements. Since each trial required about 2-1/2 hours, the three trials were accomplished at different times, and the subject was allowed to rest during each trial to avoid any effects of fatigue or boredom.

The equipment was designed to yield certain experimental information. The data sought and the mathematical analysis of the data are explained in Chapter III.

CHAPTER III

DESIGN OF THE EXPERIMENT

The experiment was designed using male subjects performing a simple repetitive task in the horizontal plane. This chapter includes a description of the task, the restrictions placed on the experiment, the measurements made from the experiment, and the computational procedure used to analyze the measurements obtained.

Subjects

Three subjects were used in the experiment; all were male and were graduate students in the Industrial Engineering Department. Four limiting factors were placed on all subjects; they were: (1) must be right-handed, (2) must be males, (3) must weigh on or near 150 pounds, (4) must have an average build. Due to the fact that a prescribed weight of 150 pounds would limit the number of persons eligible for test subjects to an unacceptable number, a plus or minus five percent (5%) deviation was allowed. The weights of the subjects are shown in Table 2. This restricting factor allowed the use of the data found by Dempster [5] concerning the segmental weights as a percentage of total body weight of a 150 pound man (reference Appendix C). As stated in the introduction,

Dempster verified that his data provided extremely close results when tried on live subjects. With Dempster's data, the weights of the various segments of the subject's arm can be determined.

TABLE 2

SUBJECT WEIGHT

Subject	Weight
1	156 lbs.
2	155 lbs.
3	145 lbs.

The restricting factor of all male subjects was included because Dempster's data were determined from male cadavers, and for this reason any experiments using these data should be restricted to male subjects. A practical reason for using all male subjects was that the availability of male students for subjects greatly exceeded the availability of female subjects. The requirement that all subjects be right-handed was included because the experiment was limited to analyze movements by the right hand only. The requirement that all subjects be of average build was included because Dempster states that the human arm has the same general shape and that for this reason his data can be applied to general problems dealing with the center of gravity of the body and its segments. The

average arm, for the purpose of this thesis, is one with no noticeable deformities.

Anthropometric Dimensions

The anthropometric dimensions used in this experiment will be the actual dimensions of the subject's arm "links." There are three of these to be measured; they are: (1) the upper arm link, (2) the forearm link, and (3) the hand link. The arm links and their axes of rotation or joint centers are described in Appendix B in reference to visual body surface landmarks so that physical measurement of the link is possible. The body landmarks associated with the joint centers are as follows:
(1) shoulder--mid-region of palpable bony mass of head;
(2) elbow--lowest palpable point of medial epicondyle;
(3) wrist--(dorsal surface) palpable groove between lunate and capitate bones. The procedure used to measure the subject's arm link dimensions will be described later in the chapter under the section of measurements.

Arm Segments' Centers of Gravity

The location of the center of gravity of the segments of the subject's arm will be found by the use of Dempster's data (reference Appendices A, B, and D). Dempster lists the location of these points with verbal descriptions and in terms of percentage distance from the proximal to distal axes of rotation. The subject's "link"

dimensions will be physically measured, and the point of the center of gravity on the link will be calculated by use of the information referenced above. The point of the center of gravity on the link will be marked with a strap around the point on the upper arm, forearm, and hand.

The fact that the data obtained by Dempster in his experiment were constant to within one percent (1%)--and he concludes that his data can serve as constants for general work with the center of gravity--provides justification for this method of determining the segment centers of gravity. From the location of the segment centers of gravity the location of the position of the center of gravity of the total arm can be found. This procedure will be explained in a later section.

Task

The task involved is moving a cylindrical stylus along a prescribed path. The total length of the move will be twelve inches. All moves will start at a point approximately nine inches in front of the subject's frontal plane and centered with his body. (See Figure 1, page 15.) The reason for the variance is that the chair on which the subjects were seated was positioned so that when the subject fully extended his arm the cylindrical probe would just pass over the twelve-inch mark on the prescribed path which corresponds to the seventh contact,

when the prescribed path is located at 90 degrees to the subject's body (reference Figure 2, page 16). The length of the move was chosen to obtain an approximately full extension of the arm during the 90 and 135 degree moves. It was realized that the arm would not be fully extended during the 45 and 0 degree moves. However, since the actual length of move is the same in all directions and the work place was designed to simulate the work place of a seated worker, sufficient justification exists for establishing the dimensions of the task in the prescribed manner.

The starting point corresponds with the first electrical contact of the electrical path board as shown in Figure 3, page 18. Four separate moves were performed; they are: one at 90 degrees to the subject's frontal plane, one at 45 degrees to the frontal plane, one parallel to the frontal plane, and one perpendicular to the 45 degree move which was at an angle of 135 degrees to the subject's frontal plane when measured in the counterclockwise direction. The directions of move were chosen so that a symmetrical representation of the movement of the center of gravity over the entire work area could be made.

Measurements

To analyze the path traveled and the velocity of the center of gravity of the total arm during a simulated

industrial move, certain characteristics must be known. These characteristics are: (1) the coordinates of location of the total arm center of gravity at the beginning of a move, at certain incremental distances of the move, and the end of each move; (2) the coordinates of location of each arm segment center of gravity at the beginning of a move, at certain incremental distances of the move, and the end of each move; (3) the time for the total move and the incremental distance; (4) the "link" dimensions of the subject's arm. The following paragraphs explain how the equipment was designed to obtain these characteristics.

Link Dimensions

The subject's link dimensions were obtained by physically measuring the link. The procedure used was to locate the body surface landmarks associated with the joint centers and to measure the distance between these joint centers. A tape with a scale of 1/4 inch was used to take the measurements. The link dimensions of the subjects are shown in Table 3. Table 3 also shows Dempster's estimate of link dimensions on living subjects. A comparison of these figures shows that the subjects used in this experiment compare favorably with the Dempster estimates.

The link dimensions were used to obtain each arm segment's center of gravity. The reference point for the upper arm and the forearm was the lowest palpable point of

the medial epicondyle of the humerus. The medial epicondyle was used because it is the easiest to locate of the body surface landmarks. By using one reference point for both the forearm and upper arm location of the center of gravity, any error made in the location of the referenced centers will be constant. Since three trials were made it was also easier to locate the radius indicators at the same spot on the arm for each trial. Figure 11 shows the arm segments and the reference points indicated by Dempster. Table 4 gives the location of each segment center of gravity for each subject.

TABLE 3

SUBJECT LINK DIMENSIONS

Subject	Link	Length (inches)
1	Upper Arm	12.0
	Forearm	11.0
	Hand	3.1
2	Upper Arm	11.4
	Forearm	10.2
	Hand	2.5
3	Upper Arm	11.5
	Forearm	10.5
	Hand	2.7

Dempster's Estimate of Link Dimensions

Link	50th Percentile
Upper Arm	11.9
Forearm	10.7
Hand	2.8

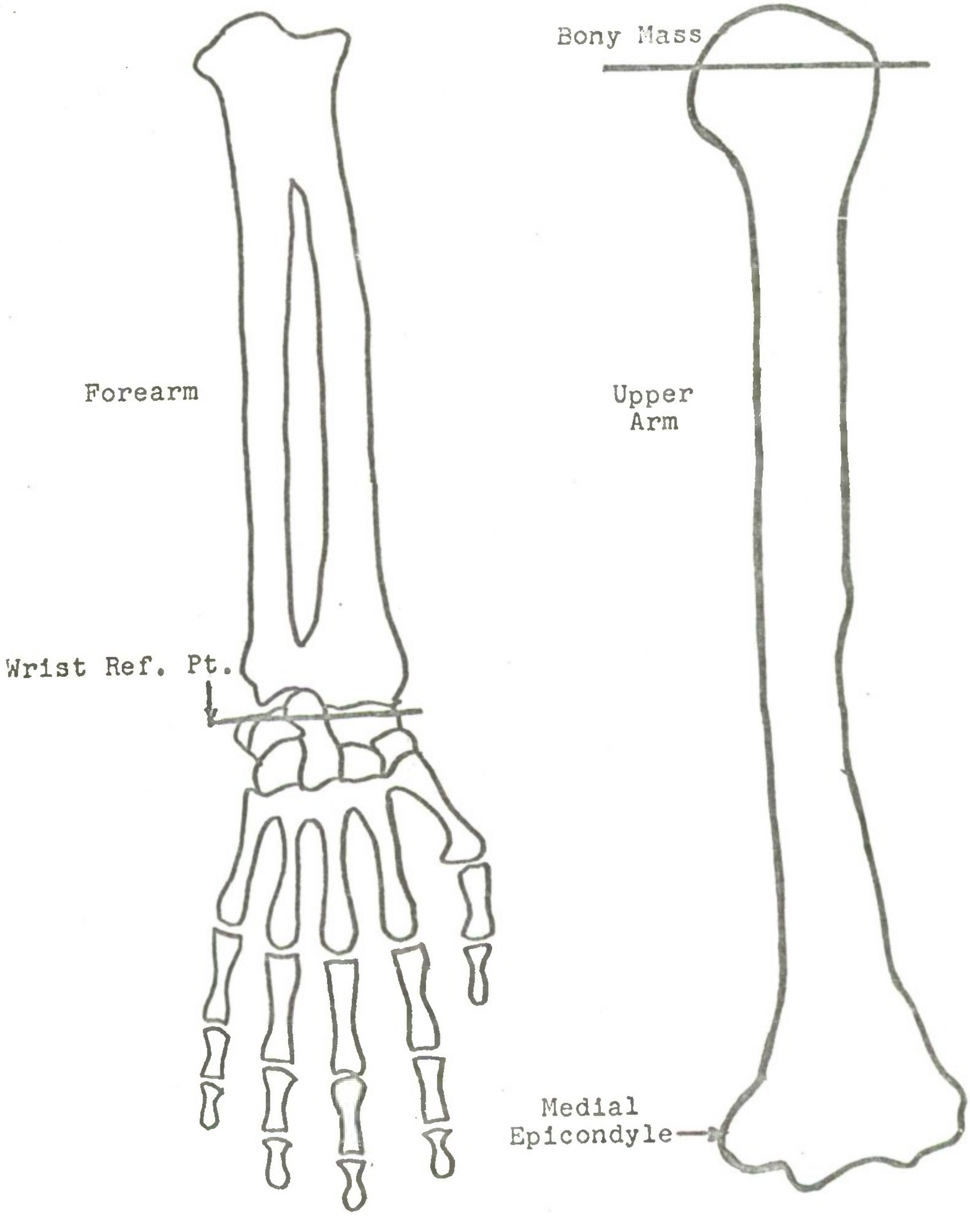


Fig. 11.--Arm segment reference points

TABLE 4

LOCATION OF SEGMENT CENTER OF GRAVITY

Subject	Segment	Location
1	Upper Arm	6.77 inches up from medial epicondyle
	Forearm	4.73 inches down from medial epicondyle
	Hand	2 mm proximal to proximal transverse palmar skin crease
2	Upper Arm	6.43 inches up from medial epicondyle
	Forearm	4.38 inches down from medial epicondyle
	Hand	2 mm proximal to proximal transverse palmar skin crease
3	Upper Arm	6.48 inches up from medial epicondyle
	Forearm	4.51 inches down from medial epicondyle
	Hand	2 mm proximal to proximal transverse palmar skin crease

The hand center of gravity is the easiest to locate. It is given by Dempster as on the axis of metacarpal III, 2 mm proximal to proximal transverse palmar skin crease, in angle between proximal transverse and radial longitudinal crease. The distance from the joint center of the wrist to the center of gravity was measured on the palmar surface; then the same distance was laid off on the dorsal surface, thereby locating the center of gravity on the top of the hand.

Spherical Coordinates

To locate a point in space, some form of coordinate system must be used to define the location. Spherical

coordinates were used in this experiment to locate each segment's center of gravity and to define the location of the total arm center of gravity. Spherical coordinates were more advantageous than the rectangular system because equipment could be designed to read spherical coordinates directly while the rectangular system presented rather difficult design procedures. Therefore, spherical coordinates were used to facilitate the design of the equipment and because it was felt that spherical coordinates lead to more accurate measurements. The method of operating the equipment to obtain the spherical coordinates was explained in Chapter II under the section describing the angle gauge.

The spherical coordinates were used to determine the location of the center of gravity of the total arm at each of the seven contacts on the path of motion. By assuming that the center of gravity travels in a straight line motion between each set of coordinates, the total distance traveled by the center of gravity can be found by summing the incremental distances.

The spherical coordinates were converted to Cartesian coordinates for actual calculations and to facilitate plotting the path followed by the total arm center of gravity. The exact procedure used to find the total arm center of gravity from each segment center of

gravity will be explained in the mathematical procedure section of this chapter.

Three trials were run for each subject in each direction so that values obtained for each trial could be calculated and the results averaged. Three trials were decided sufficient to obtain a representative average in this experiment. The time available for the experiment also limited the number of trials.

Times

To evaluate the behavior of the velocity, the time for the total move and the time for each incremental distance were necessary. These times were taken for each move and trial as explained in Chapter II. The mathematical procedure used to find the velocity is explained in the next section.

Mathematical Procedure

The first step in the mathematical procedure used in this experiment was to convert the spherical coordinates of the center of gravity of the hand, forearm, and upper arm to rectangular coordinates. Trigonometric formulae were used to accomplish this conversion. The spherical coordinates were in the form of R, α, and θ. The following formulae were used to convert to rectangular coordinates:

$$\begin{aligned} X &= R\,(\cos\alpha)\,(\sin\theta) \\ Y &= R\,(\cos\alpha)\,(\cos\theta) \\ Z &= R\,(\sin\alpha) \end{aligned} \tag{1}$$

where

X, Y, & Z = rectangular coordinates
R, α, & θ = spherical coordinates

The second step in the mathematical procedure was to find the total arm center of gravity from the segments' centers of gravity. This was found by the principle of summing moments about an axis. We now know the rectangular coordinates of each segment's center of gravity and the weight of each segment so the coordinates of the center of gravity can be found by calculating the weighted average of the positions of the three segments, using segment weights. The following example of the X coordinate illustrates the procedure:

X_R = X coordinate of total arm center of gravity

X_1 = X coordinate of the hand center of gravity

X_2 = X coordinate of the forearm center of gravity

X_3 = X coordinate of the upper arm center of gravity

W_H = weight of the hand segment

W_F = weight of the forearm segment

W_u = weight of the upper arm segment

X_R is then found by the formula:

$$X_R = \frac{W_H \circ X_1 + W_F \circ X_2 + W_u \circ X_3}{W_H + W_F + W_u} \tag{2}$$

The Y and Z coordinates of the total arm center of gravity are found in the same manner. It should be emphasized that the rectangular coordinates for the total arm center of gravity are calculated for each contact on the path of travel of the move.

The third step in the mathematical procedure was to determine the total distance traveled by the center of gravity during each move. To find this distance it was assumed that between each contact or set of location coordinates the center of gravity traveled in a straight line. Since there were seven contacts, there were six intervals of travel. To calculate the distance between points, the following formulae were used:

$$X_i,\ Y_i,\ Z_i, = \text{coordinates of center of gravity at contact } i \qquad (3)$$

where

$$i = 1, - - - - , 7$$

Distance traveled by center of gravity while hand travels from contact i to contact i + 1 is given by:

$$\text{Dis} = \sqrt{(X_{i+1}-X_i)^2 + (Y_{i+1}-Y_i)^2 + (Z_{i+1}-Z_i)^2} \qquad (4)$$

Using this procedure for each increment of travel and then summing the increments gives the total distance traveled by the total arm center of gravity during each move.

The fourth step in the mathematical procedure was to find the incremental velocity and the average velocity of the center of gravity. Since the incremental distances and total distance traveled by the center of gravity are now known and the time for each increment and total time are known, the velocity for each increment of travel and total travel can be found by the formula of distance divided by time equals velocity.

All mathematical operations were performed on the IBM 1620 computer. A general Fortran computer program was written to perform all operations. A copy of the program is contained in Appendix E. The results of these procedures are reported in Chapter IV. The implications of the results and conclusions are reserved for Chapter V.

CHAPTER IV

RESULTS

As was stated in Chapter III, the equipment and experiment were designed to yield certain data that would be used to analyze the path and distance traveled and the velocity of the arm center of gravity during certain simulated industrial moves. The results are presented in this chapter. Table 5 lists the results obtained in the order of presentation.

TABLE 5

ORDER OF PRESENTATION OF RESULTS

Result	Page No.
Distance Moved	49
Path of Travel	55
Velocity	68
Average Increment	68
Average Total	82
Maximum Velocity	89
Hand Velocity	89

Distance Moved

One of the primary purposes of the investigation was to determine the distance and path traveled by the center of gravity during the moves considered. The distance traveled by the arm center of gravity was determined for each subject, in each direction, for three trials. The three trials were averaged, and this value was used as the distance traveled by the arm center of gravity for each subject. Figure 12 shows the distance traveled by each subject's arm center of gravity for the four moves.

As the figure illustrates, the arm center of gravity moves much less in the 0 and 45 degree moves as compared to the 90 and 135 degree moves. This is what one would expect since the upper arm is extended further in the 90 and 135 degree moves. The variation in travel between subjects was small with the 135 degree move showing the largest variation. The variation between subjects or difference between the largest and smallest distance traveled was as follows: 135 degrees--.8 inches; 90 degrees--.3 inches; 45 degrees--.5 inches; and 0 degrees--.4 inches. These small variations could possibly be caused by reading interpretation when taking data during the experiment. There is, however, a definite trend between subjects toward a constant distance traveled in each direction by the arm center of gravity. Table 6 shows the individual subject results with the associated standard

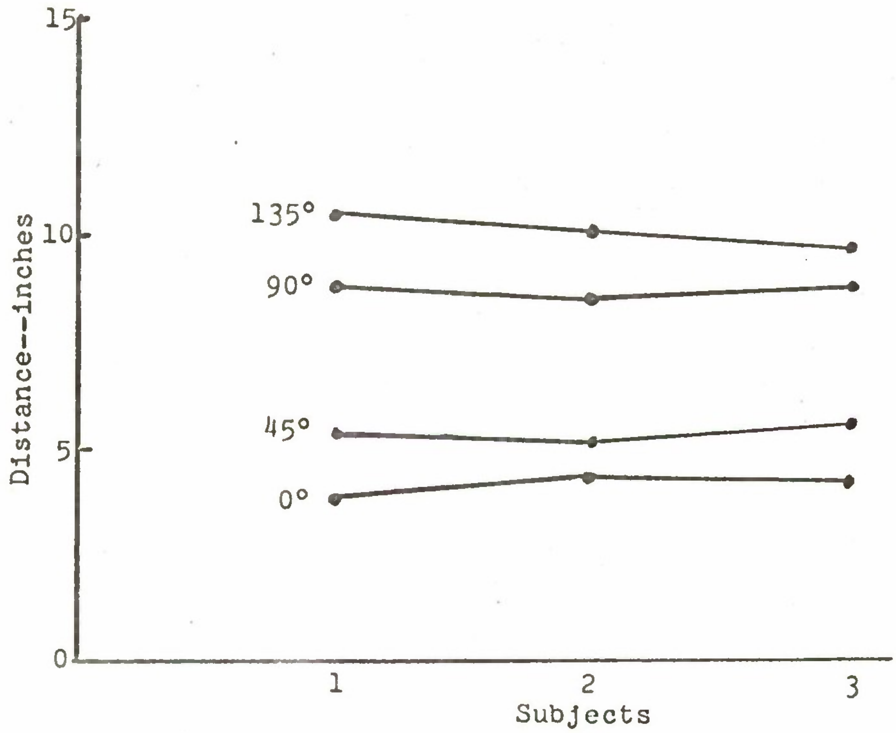


Fig. 12.--Total distance moved by the center of gravity

deviation and the average value for each direction for all subjects.

TABLE 6

DISTANCE MOVED BY ARM CENTER OF GRAVITY

Direction	Subject	Distance Moved (inches)	Standard Deviation
0°	1	3.9	.081
	2	4.3	.081
	3	4.1	.052
45°	1	5.3	.052
	2	5.1	.081
	3	5.6	.052
90°	1	8.8	.081
	2	8.5	.930
	3	8.8	.160
135°	1	10.4	.081
	2	10.0	.081
	3	9.6	.160

Direction	Average Distance Moved (inches)	Standard Deviation
0°	4.1	.16
45°	5.3	.21
90°	8.7	.15
135°	10.0	.32

Figure 13 shows a symmetrical plot of the travel of the arm center of gravity. Only the points where the curve intersects the direction axes have been verified by the results of the experiment. By drawing smooth curves between the known points, the figure shown in Figure 13 results. An unpublished work by M. M. Ayoub [15] of the Industrial Engineering Department at Texas Technological College substantiates the plot of the travel of the arm center of gravity as obtained by this experiment. Ayoub calculated and plotted the path of travel of the center of gravity of an arm moving in the horizontal plane. His results were based on the arm being flexed to 90 degrees so that all segments of the arm would move in the horizontal plane. Ayoub calculated the distance traveled for 15 degree increments, starting at an angle parallel to the frontal plane of the body and ending at an angle of 165 degrees to the frontal plane. The plot obtained by Ayoub, using two dimensions, was very similar to the plot obtained by this experiment where all three dimensions were considered. Since this experiment considered only four angles and they agree with Ayoub's results with the same angles, this would indicate that the points between the angles of this experiment would follow the same trend as did Ayoub's.

As Figure 13 indicates, the maximum distance traveled by the arm center of gravity is with moves between

Scale: 3/16" = 1"

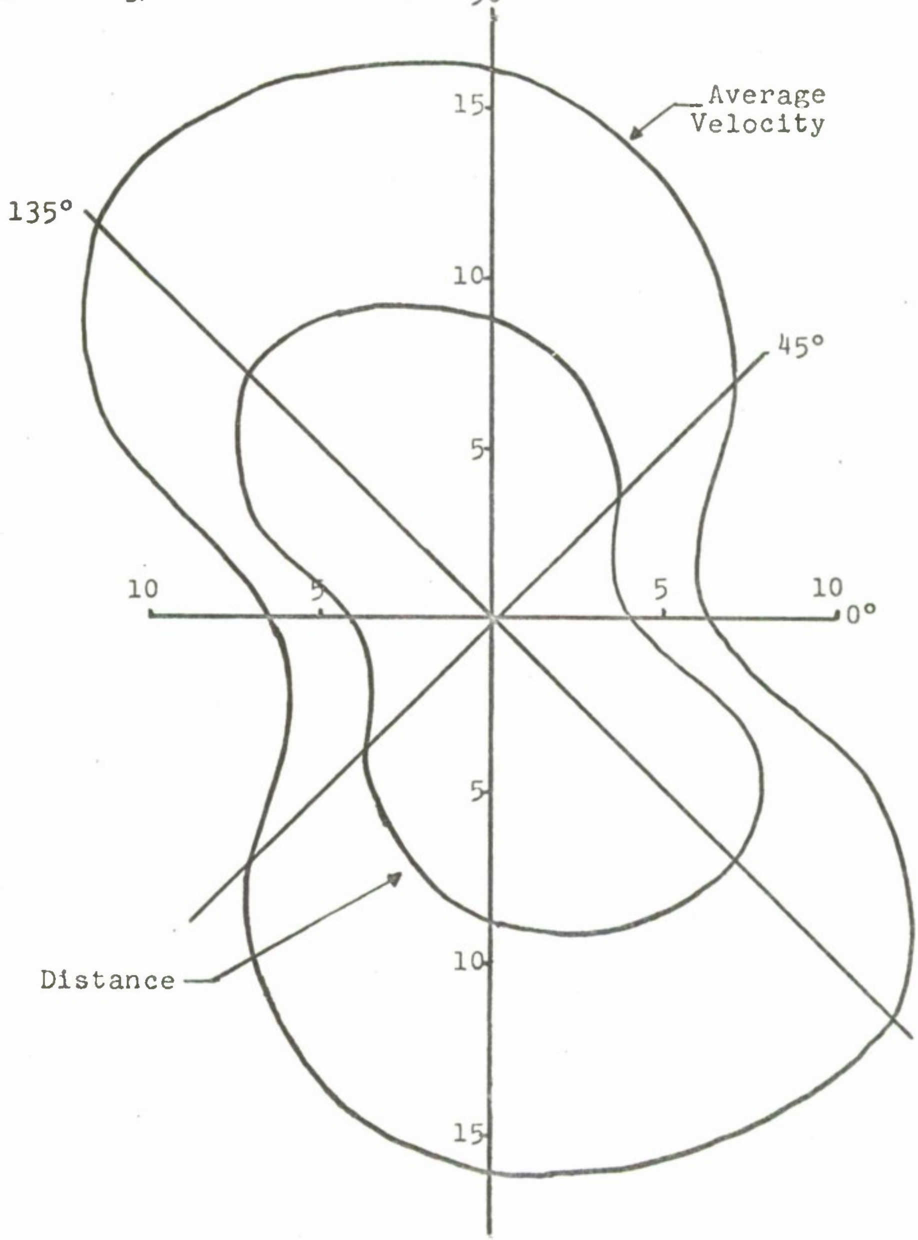


Fig. 13.--Symmetrical plot of distance traveled by center of gravity in all directions and average velocity of travel.

the 90 and 135 degree directions, with the maximum distance closer to the 135 degree direction. The minimum distance traveled is between the 0 and 45 degree directions, with the minimum closer to the 0 degree direction.

An interesting comparison can be made between the results of the plot of maximum distance traveled and the works of Schmidtke and Stier [16], Goodwin [17], and Wyatt [18] which dealt with the optimal work area for seated right-handed workers. Goodwin and Wyatt found an optimal direction where right-handed workers could move a greater distance in the same length of time that it took to move smaller distances in other directions. Schmidtke and Stier determined the optimal direction for right-handed motion based on time and distance moved. All three referenced studies were in agreement on the optimal area. From the results of their experiments they were able to plot time versus distance to obtain constant time lines. In the area where their constant time lines were maximum, the results of this experiment show that the arm center of gravity moves a smaller distance in comparison with the other directions. This result helps to explain why a worker can move a greater distance in the same length of time while performing in the reported optimal work area than when performing outside the work area. This result may indicate that less work is done by the worker when moving in the optimal work area, since the worker would be moving the

same mass a shorter distance. The result also offers a basis for defining the optimal work area for a seated worker, using a criterion other than time.

Path of Travel

To analyze the path traveled by the center of gravity, the spherical coordinates of the arm center of gravity for each subject were determined at each two-inch increment of hand travel. It was assumed that the center of gravity travels in a straight line path between adjacent sets of spherical coordinates. To obtain the plot of the travel of the arm center of gravity, the spherical coordinates obtained during each of the three trials were averaged for each subject and the results used to plot the path of travel.

The reference point for the rectangular coordinates was the eyelet of the angle gauge. As stated in Chapter II, the angle gauge was mounted on the right-hand side of the work area, at a distance of 26-1/2 inches from the front edge and 20-1/2 inches above the horizontal plane of the work area. Figure 14 was included to show the X, Y, and Z axes. It should be noted that a decrease in the Z coordinate represents an increase in height of the arm center of gravity in respect to the horizontal plane of the work area. A decrease in the X coordinate indicates the arm center of gravity is moving to the right. A decrease in the Y coordinate indicates the arm center of gravity is

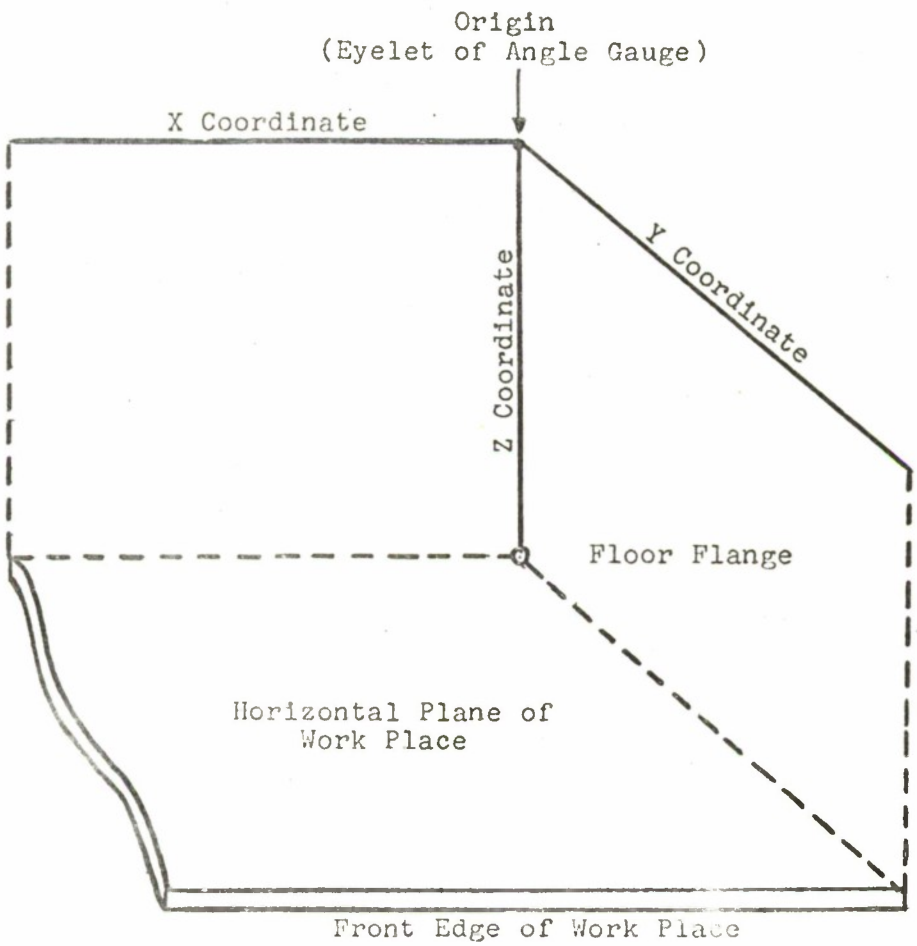


Fig. 14.--Rectangular coordinates

moving away from the worker. The graphs showing the path of travel of the arm center of gravity have a reference point A which indicates the coordinates of the arm center of gravity at the start of the move.

Figures 15A and 15B show the path traveled by the arm center of gravity during the 0 degree direction. The X-Y dimension plot represents a top view and shows that the same trend exists for each subject. The X coordinate decreases approximately 3 to 3-1/2 inches, while the Y coordinate increases approximately 2 inches. This result is what would be expected, since the direction of the move is toward the right and the upper arm tends to move backward as the hand is moved to the right. The Z-Y plot shows the change in height in respect to the horizontal plane. Two of the subjects showed a decrease in the Z coordinate, and the center of gravity followed the same pattern of travel. There is clearly a decrease in the Z coordinate as the move begins, then the arm center of gravity remains level for three to four increments of travel, and then the Z coordinate decreases again. The total change in the Z coordinate is approximately .6 inches. The third subject shows no decrease in the Z coordinate, and the center of gravity remains approximately constant throughout the move. Since the 0 degree direction is primarily a forearm movement, one would expect the height of the arm center of gravity to remain almost

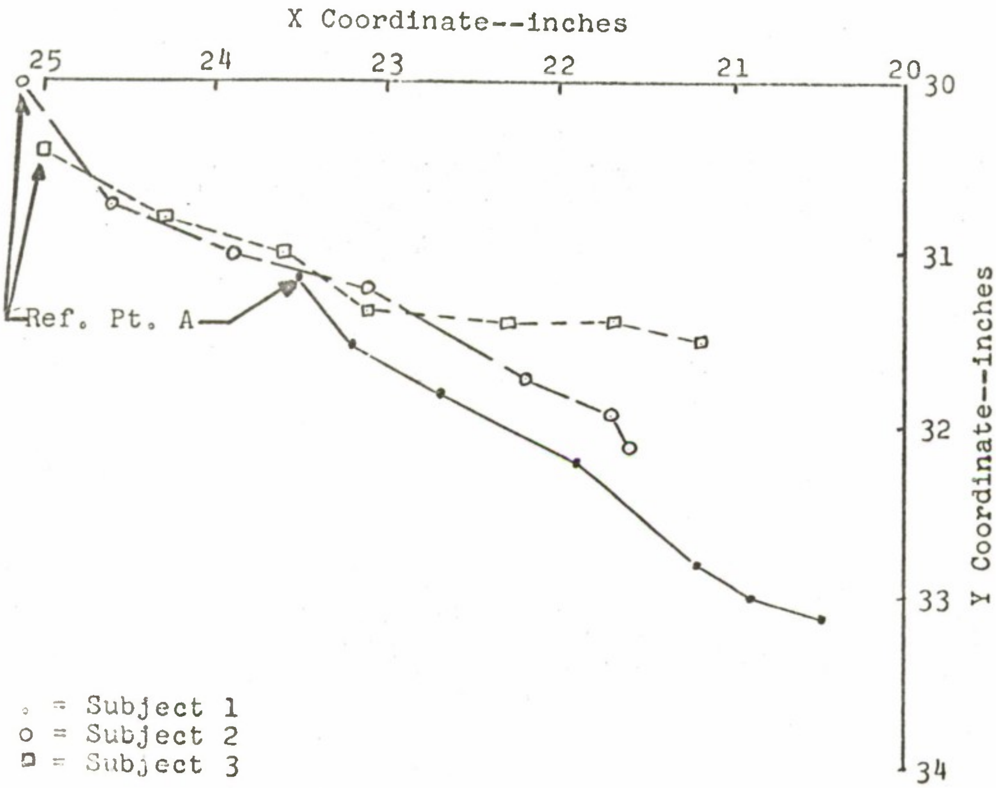


Fig. 15A.--Path of travel of the arm center of gravity 0°, X-Y plane.

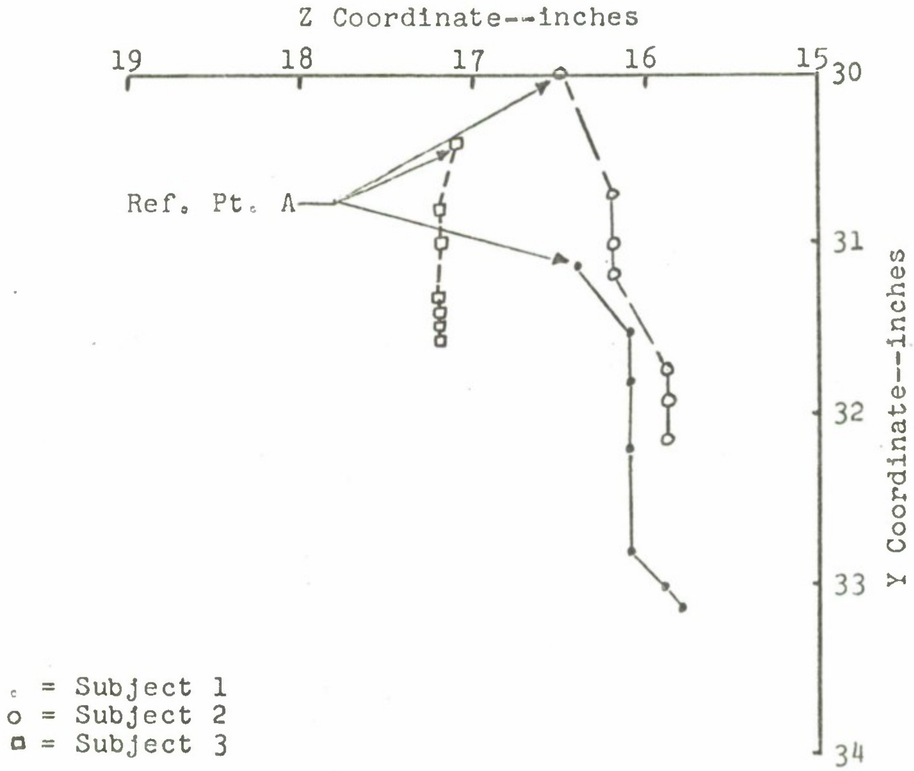


Fig. 15B.--Path of travel of the arm center of gravity 0°, Z-Y plane.

constant. The results indicate that there is very little change in the Z coordinate. It is suspected that the variation between subject 3 and subjects 1 and 2 resulted because of a difference in the shoulder motion used for the move.

Figures 16A and 16B show the path traveled by the arm center of gravity for each subject during the 45 degree move. The X-Y plot shows that the X coordinate decreases approximately 2 inches, while the Y coordinate decreases approximately 4 inches. Each subject has the same general trend, and the trend shown is what one would expect since the arm is moving toward the origin. The Y-Z plot shows the Z coordinate change during the move. Again, two of the subjects show the same trend of a decrease in the Z coordinate of the arm center of gravity during the move. The decrease shown is approximately 1 to 1-1/2 inches. The third subject shows a decrease in the Z coordinate, but the decrease is of the nature of .5 inches. Again, the variation between the subjects could be attributed to differences in shoulder movement. There is, however, a definite trend toward a decrease in the Z coordinate of the arm center of gravity during the 45 degree move, and this is expected since the move involves an extension of the total arm.

Figures 17A and 17B show the path of travel of the arm center of gravity during the 90 degree move. All

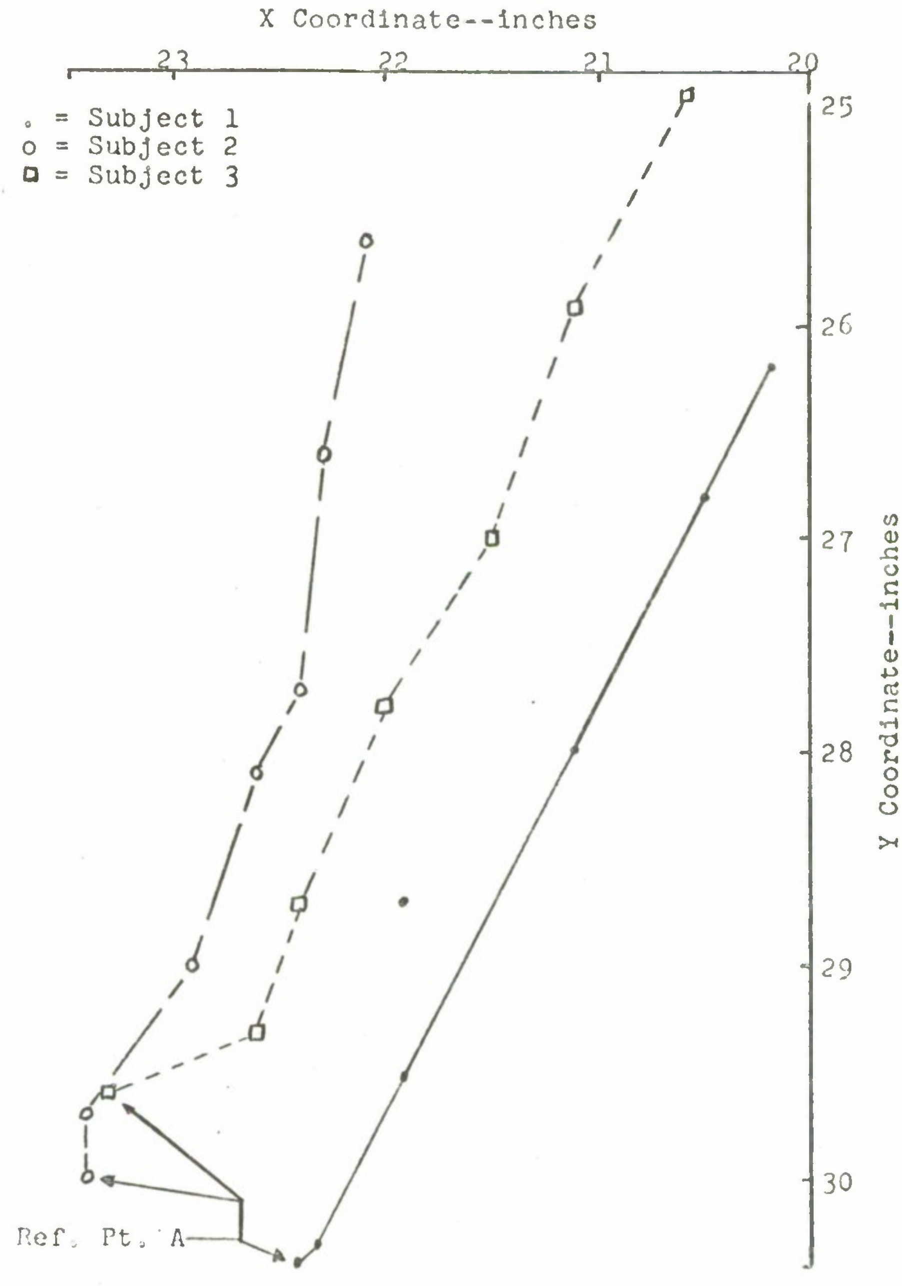


Fig. 16A.--Plot of path of travel of the arm center of gravity--45°, X-Y plane.

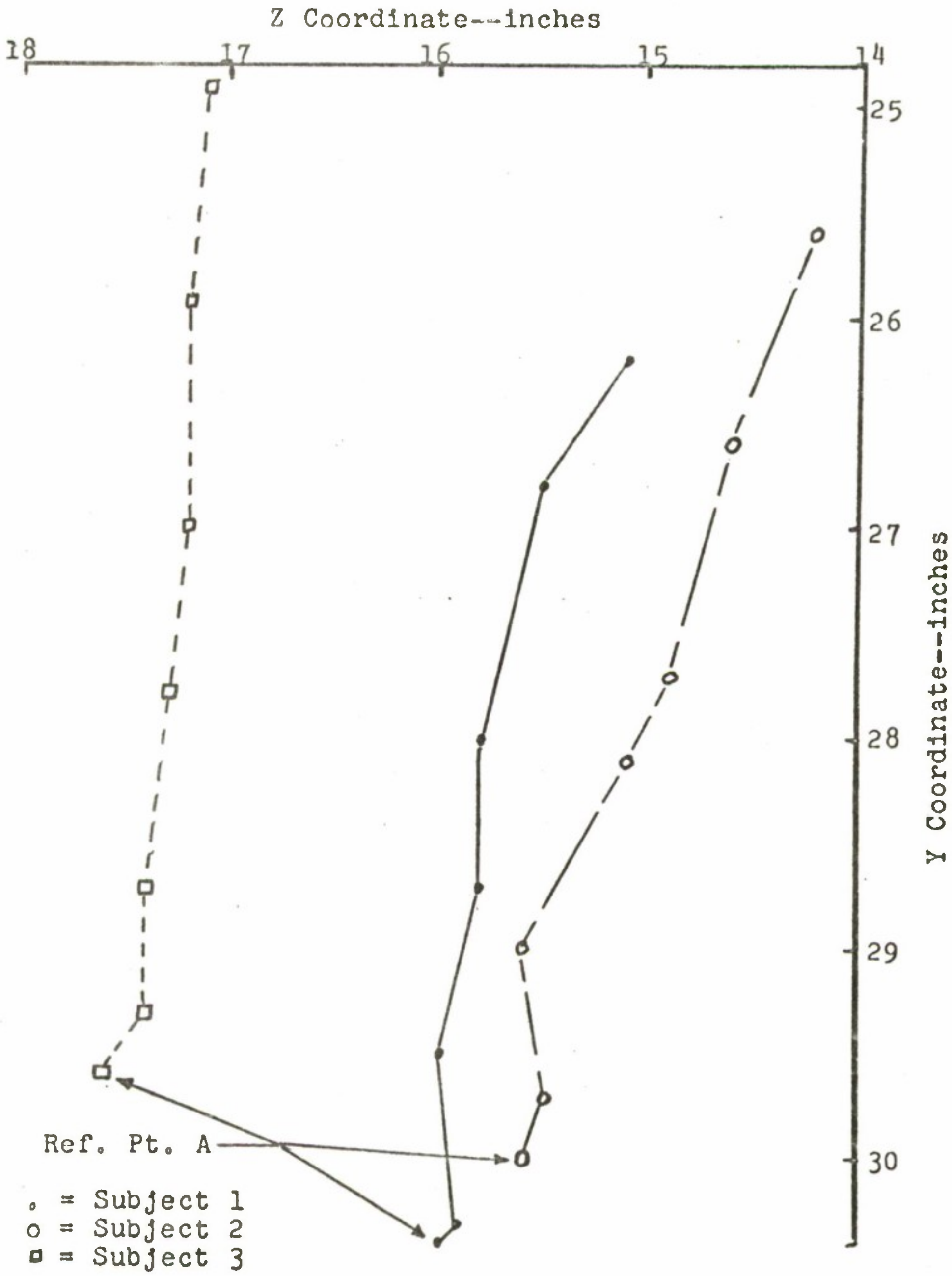


Fig. 16B.--Plot of path of travel of arm center of gravity--45°, Z-Y plane.

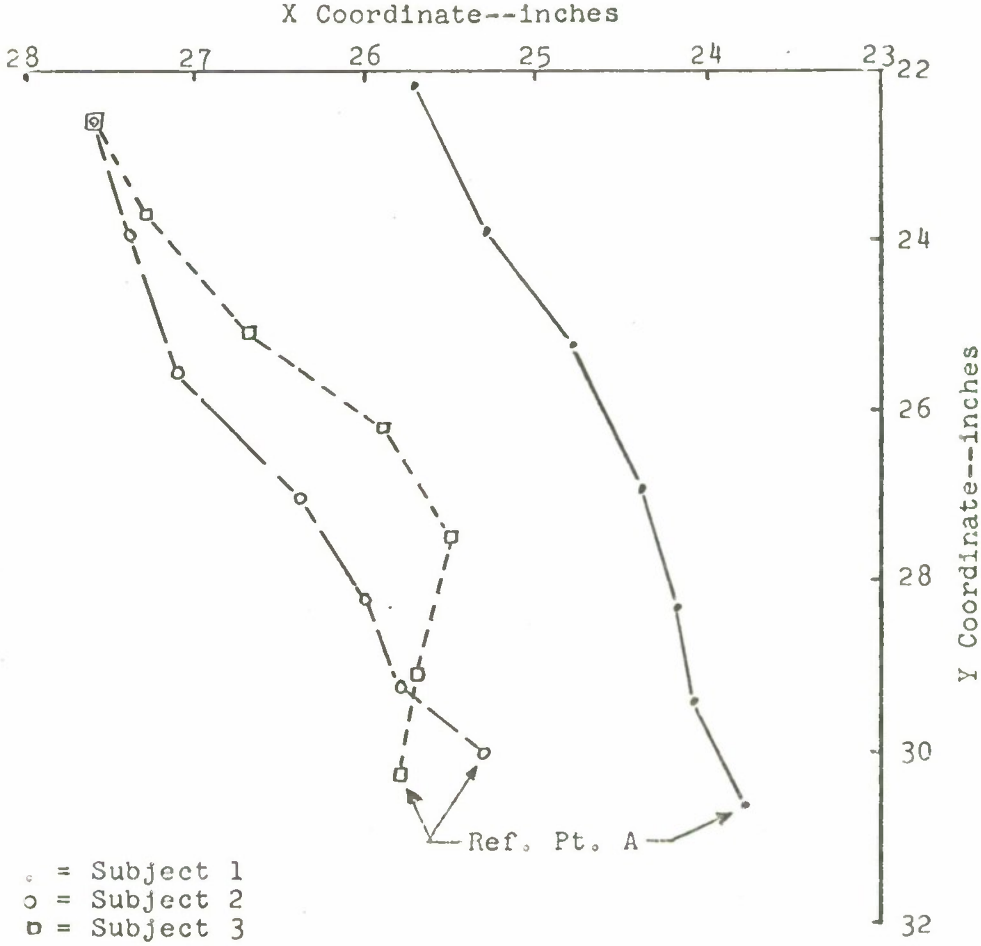


Fig. 17A.--Path of travel of arm center of gravity--90°, X-Y plane.

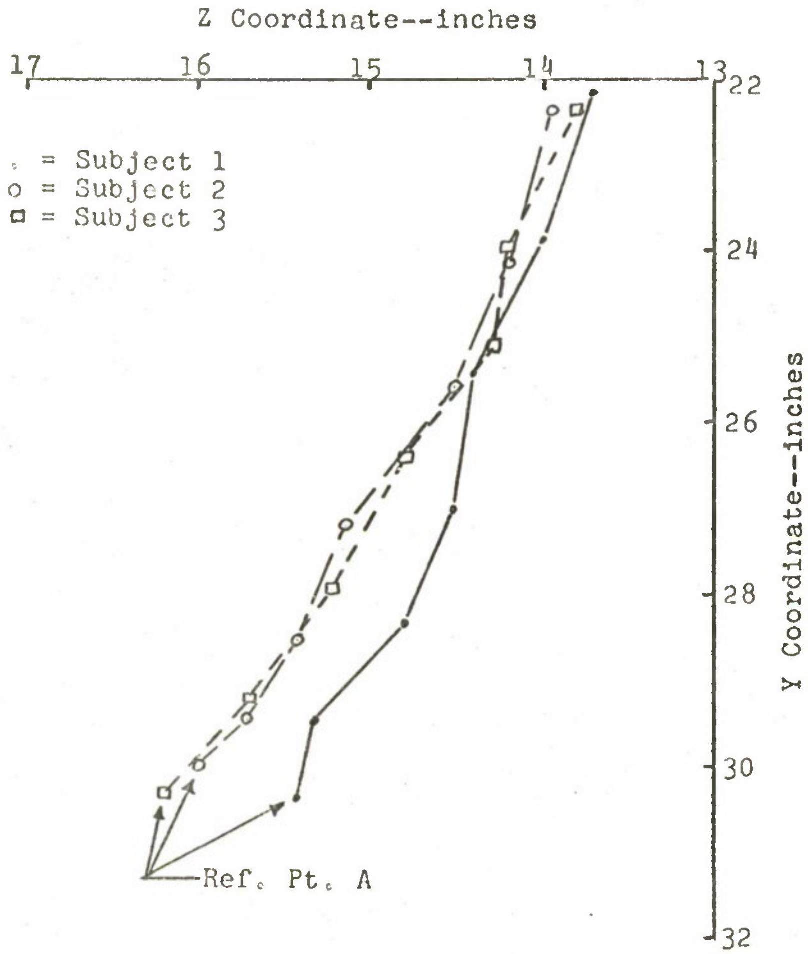


Fig. 17B.--Path of travel of arm center of gravity--90°, Z-Y plane.

three subjects show the same general trend. The X-Y plot shows that the X coordinate increases approximately 1 inch, while the Y coordinate decreases approximately 8 inches. One would expect this since the arm is fully extended during the move and the upper arm moves slightly to the left. The Z-Y plot shows that the change in the Z coordinates is very close between subjects. The plot indicates a decrease in the Z coordinate of approximately 2.2 inches during the move. This increase is expected since the upper arm is extended during the move.

Figures 18A and 18B show the path of travel of the arm center of gravity during the 135 degree move. The X-Y plot shows the same general trend of an increase in the X coordinate and a decrease in the Y coordinate. This result is expected since the arm is moving to the left and is fully extended during the move. The Z-Y plot shows that the Z coordinate of the arm center of gravity decreases during the move; this is true for all three subjects and is what would be expected since the arm is being extended.

It should be noted that even though the plots of the travel of the arm center of gravity showed the same trend, they had different values. This is due to the subjects' having different arm link dimensions, and an identical plot is not expected. The plots, however, were similar.

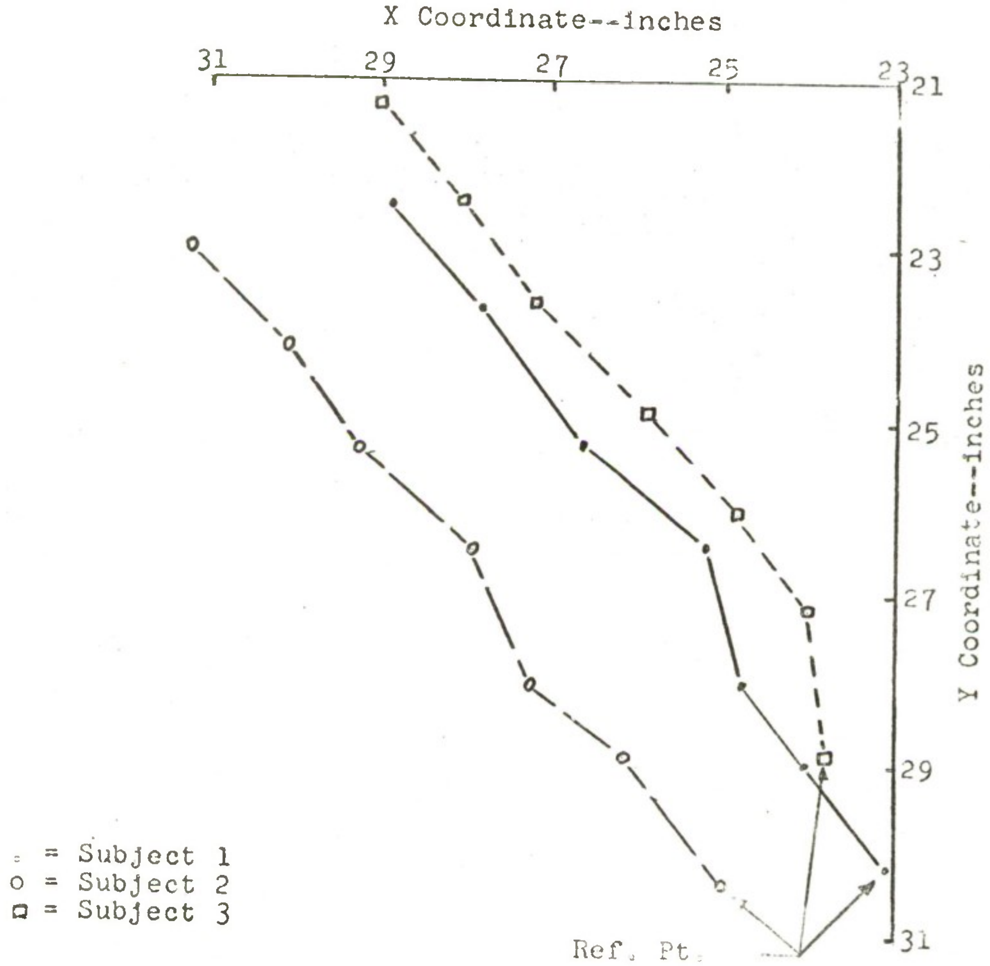


Fig. 18A.--Path of travel of arm center of gravity--135°, X-Y plane.

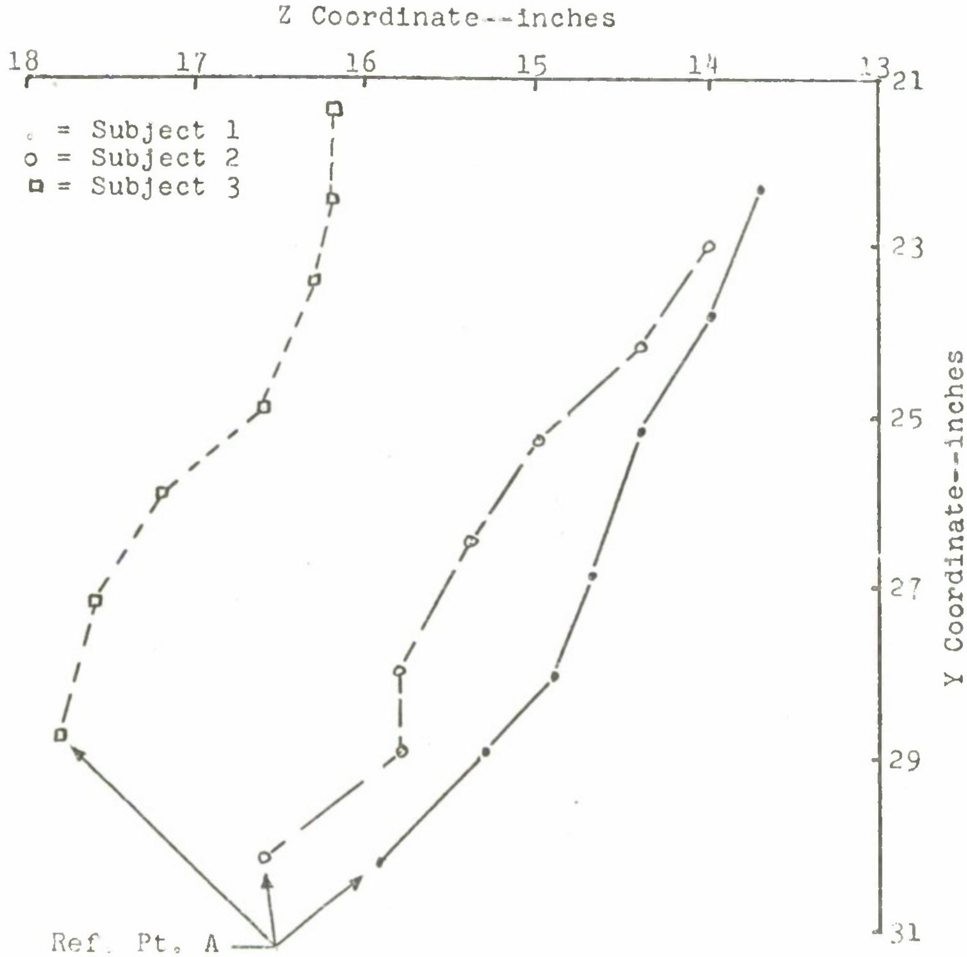


Fig. 18B.--Path of travel of arm center of gravity--135°, Z-Y plane.

Velocity

The velocity of the arm center of gravity was investigated to determine the average velocity for the total move and the increment velocity during the move. An investigation of increment velocity allows an estimate of the maximum velocity attained during a move to be determined.

Average increment velocity

Figures 19, 20, and 21 show the increment velocity for subjects 1, 2, and 3 respectively, for all three trials in the 0 degree direction. These figures indicate that each subject moved at almost the same velocity for each trial. The velocity peaked during the fourth increment of travel for each subject, then dropped for the last two increments. A point-by-point comparison shows some variation between subjects, and this is attributed to the subjects' moving at a slightly different rate even though a metronome was used; however, the variation is small. Subject three has a very small increase in velocity at increment 3, whereas the other two subjects' velocity increased considerably during increment 3. This variation is attributed to a subject characteristic of starting to move fast, then slowing up to keep pace with the metronome.

Figures 22, 23, and 24 show the increment velocity for each subject during the 45 degree direction. A comparison between the plots shows that each subject followed

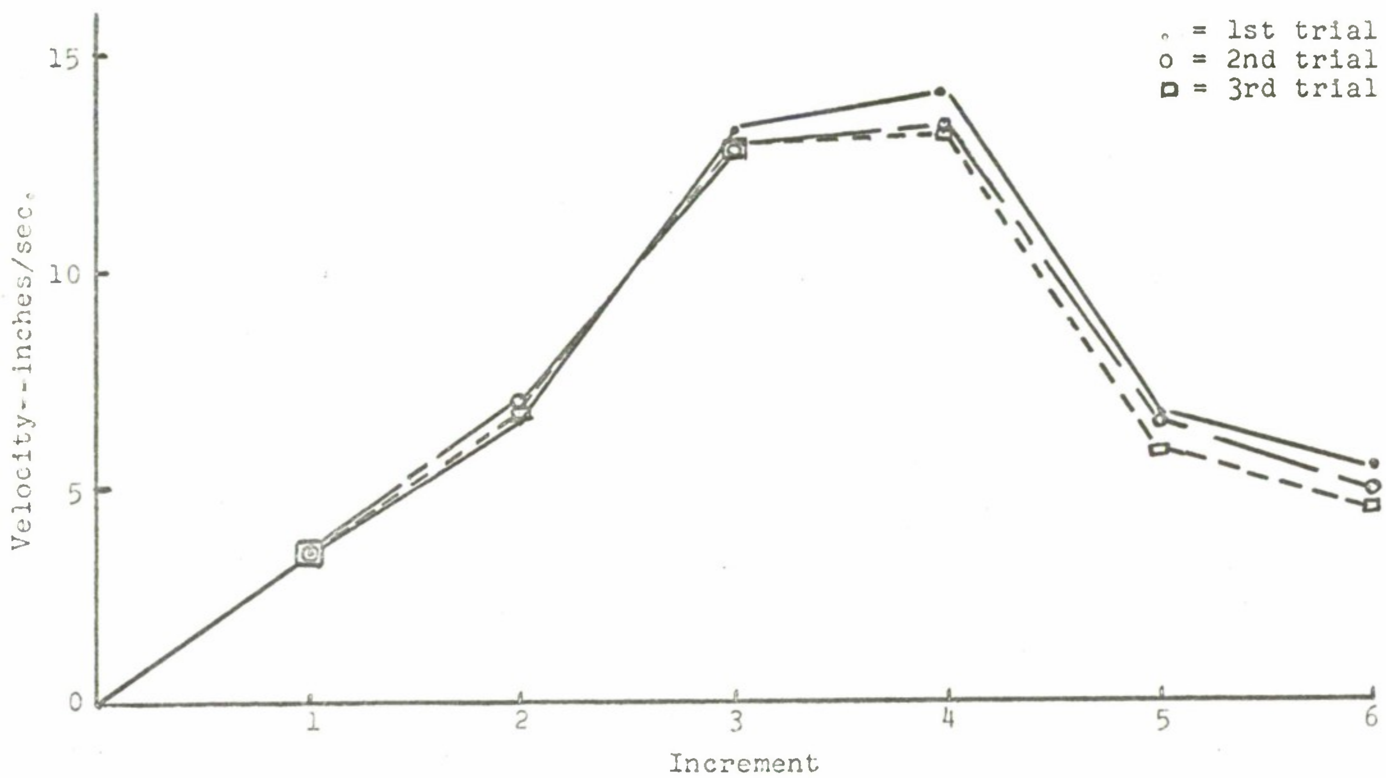


Fig. 19.--Plot of increment velocity--0°--subject 1

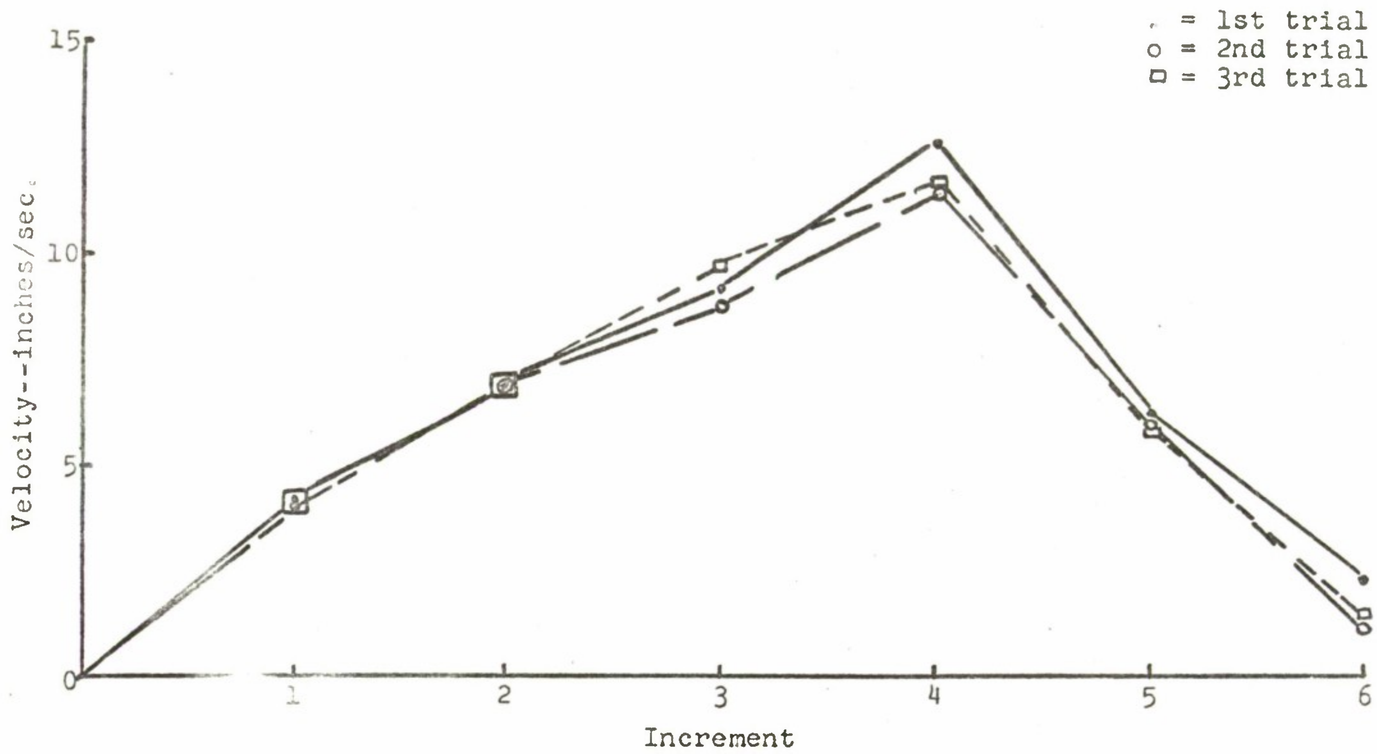


Fig. 20.--Plot of increment velocity--0°--subject 2

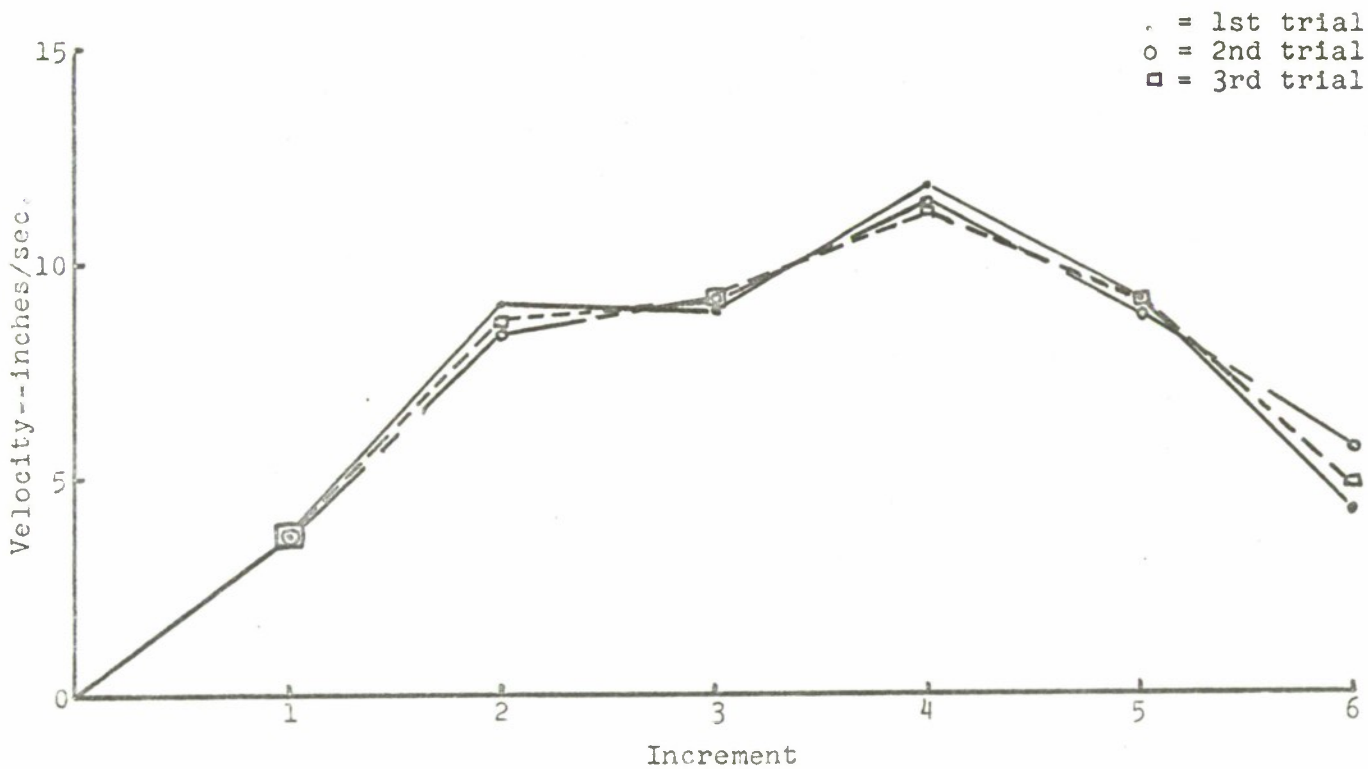


Fig. 21.--Plot of increment velocity--0°--subject 3

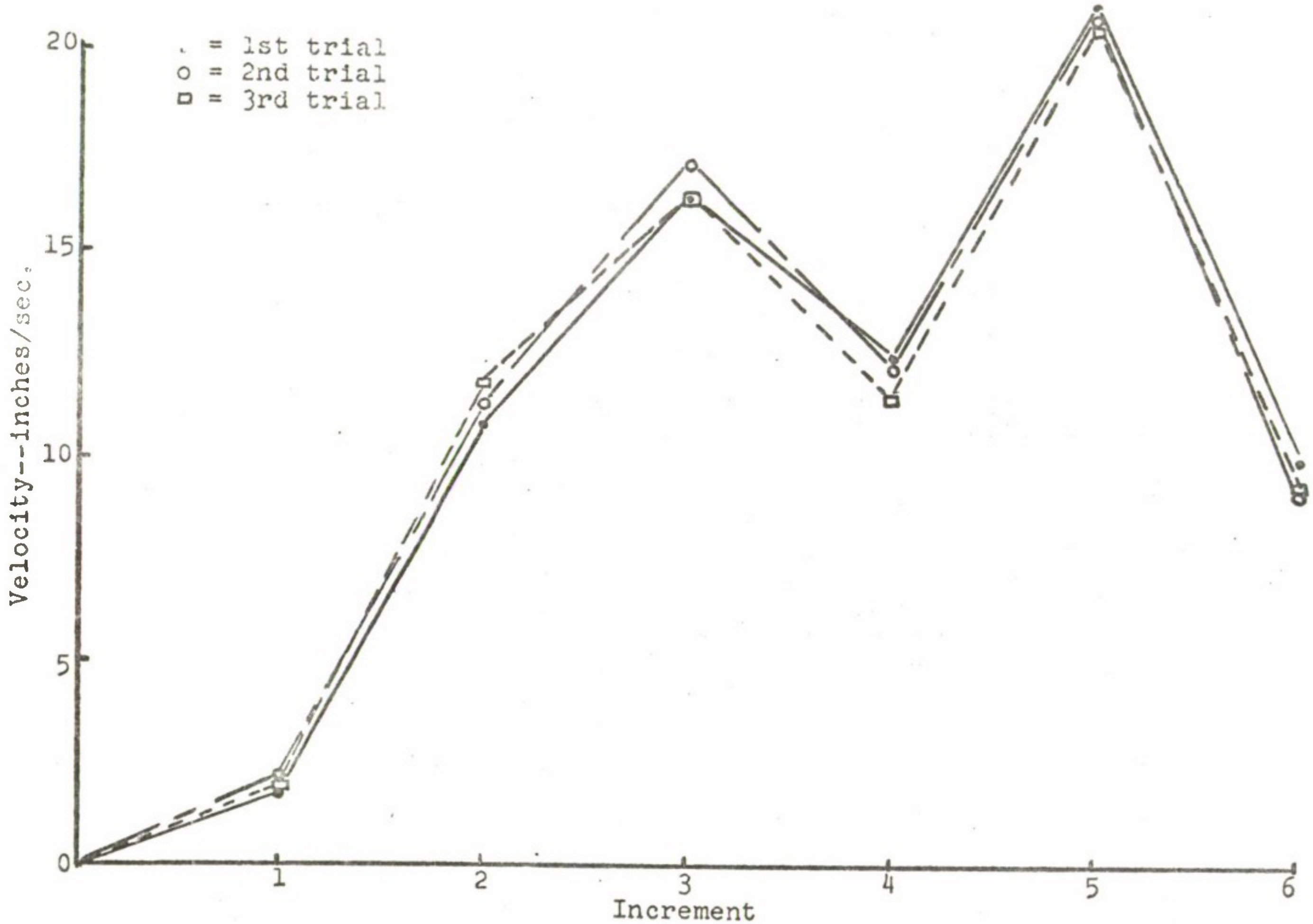


Fig. 22.--Plot of increment velocity--45°--subject 1

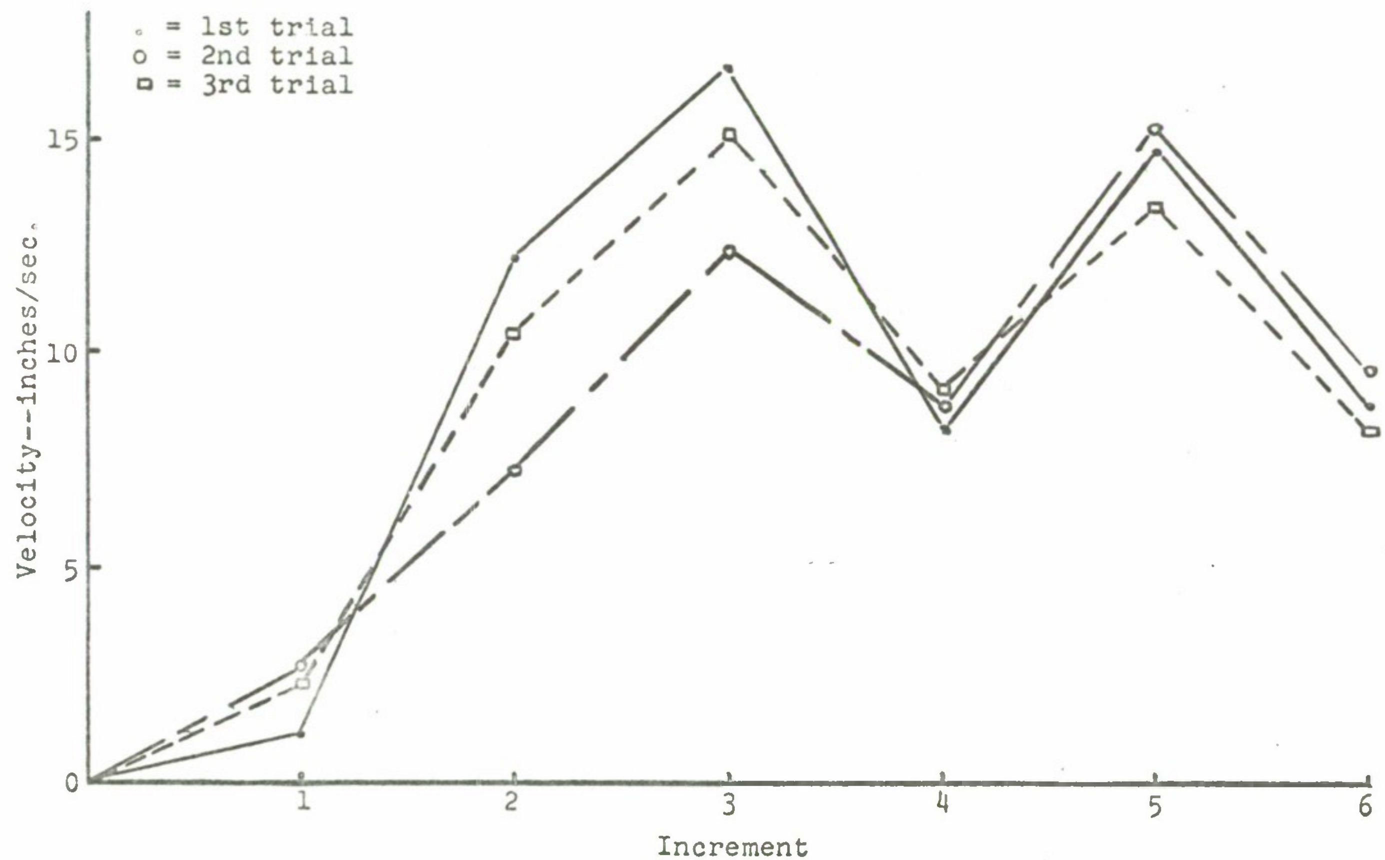


Fig. 23.--Plot of increment velocity--45°--subject 2

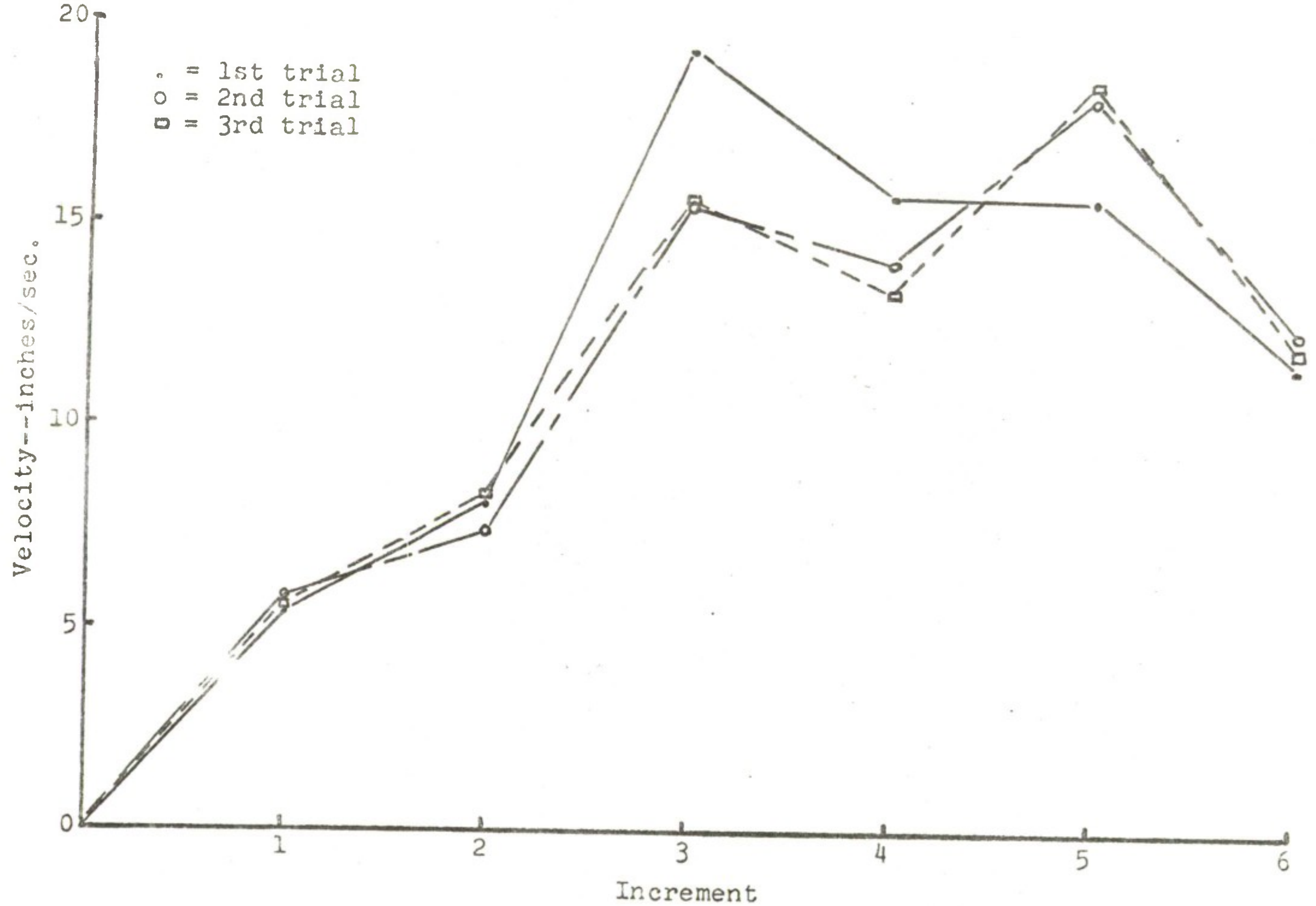


Fig. 24.--Plot of increment velocity--45°--subject 3

the same general trend. The maximum velocity was attained during the fifth increment with the third increment being only slightly lower. Characteristic with all subjects was a drop in velocity during the fourth increment. This was caused by the arm center of gravity traveling a much smaller distance during the fourth increment, yet the time for travel was almost the same as the time for the third and fifth increments.

Figures 25, 26, and 27 show the increment velocity for each subject during the 90 degree direction. Each subject showed the same trend and only small variations between trials exist. These variations are attributed to the subject's getting ahead or behind the beat of the metronome and then trying to compensate. The velocity generally peaked during the fourth increment of travel with the velocity during the fifth increment only slightly lower. It should be noted that the velocity plots for this direction are much higher than the plots for the 0 and 45 degree directions.

Figures 28, 29, and 30 show the increment velocity for each subject during the 135 degree direction. Each subject showed the same general trend with the velocity peaking during the fourth interval. Subject three shows a much higher initial velocity and then the curves flatten during the third increment. This variation is attributed to the subject's starting too fast, then attempting to

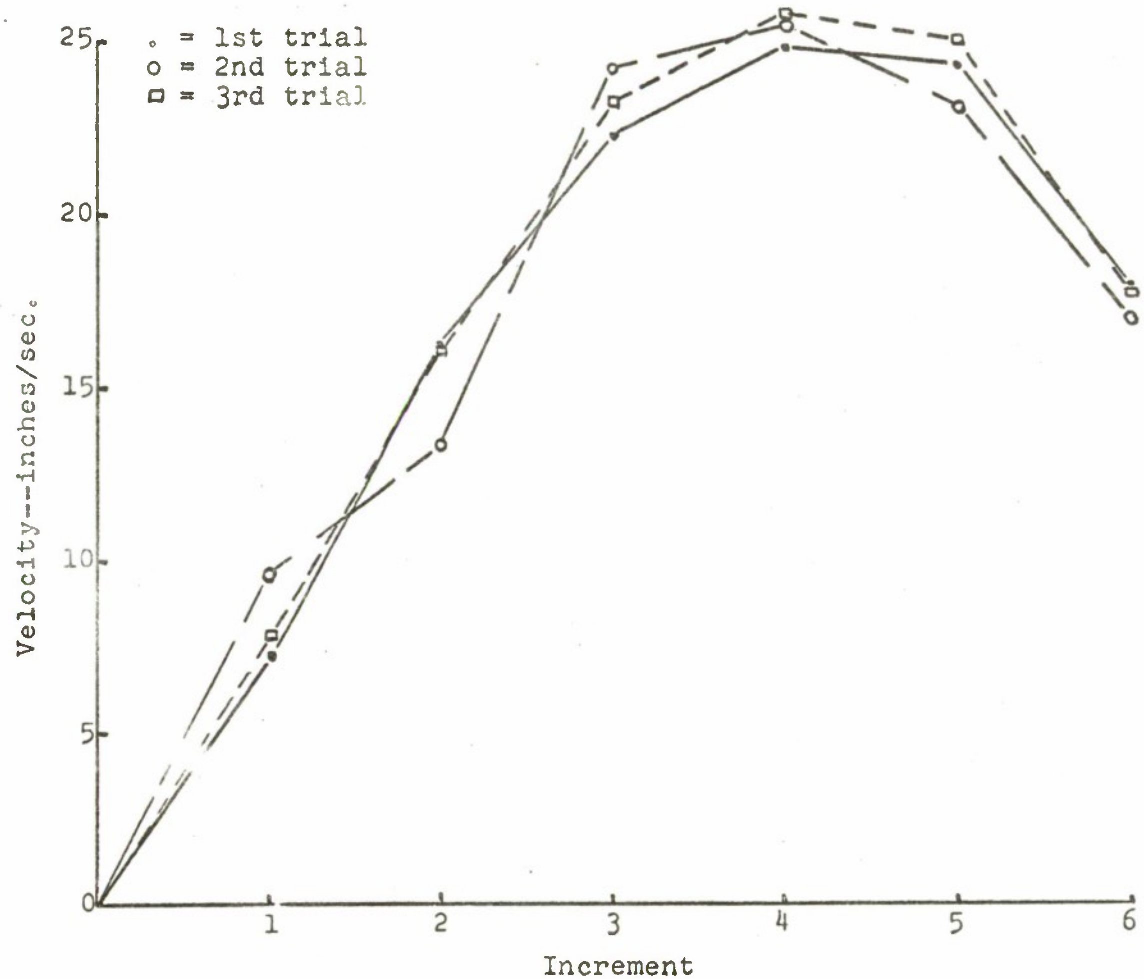


Fig. 25.--Plot of increment velocity--90°--subject 1

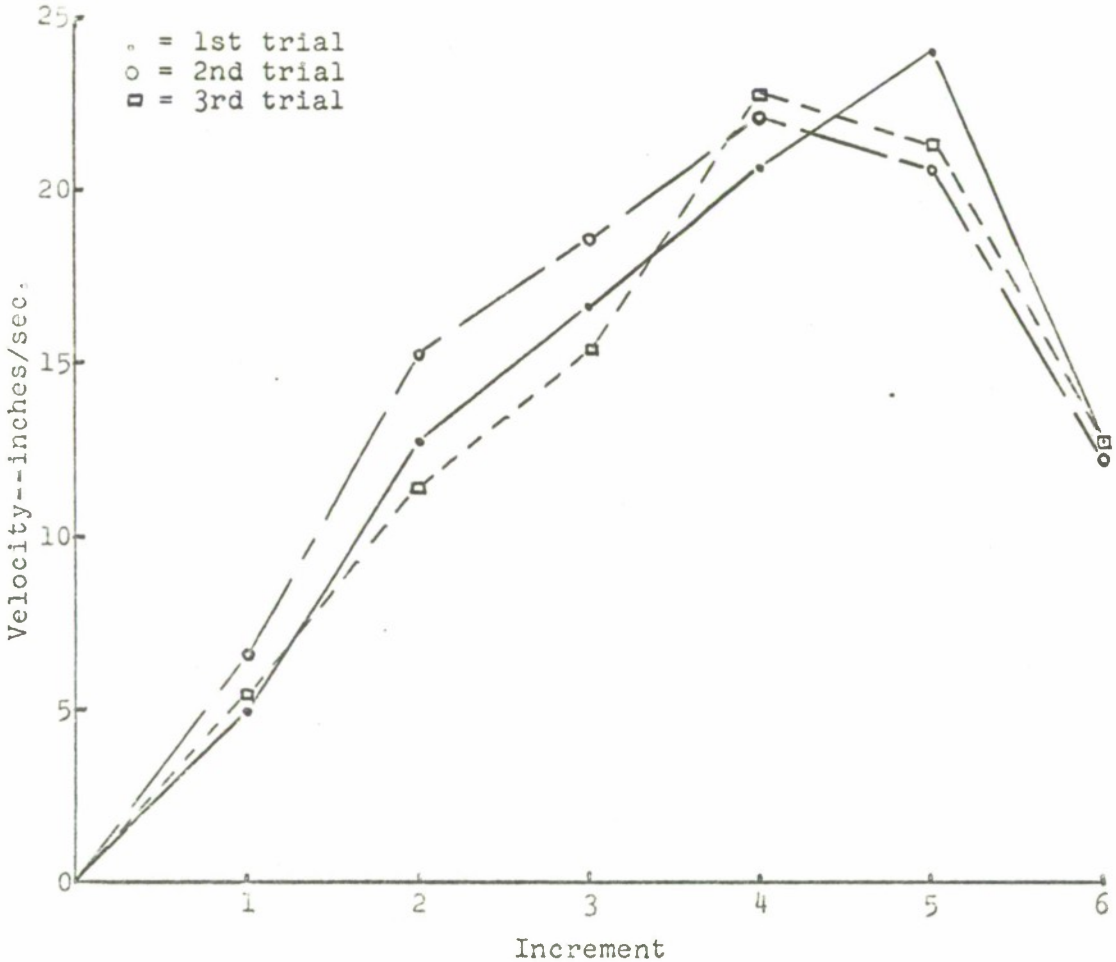


Fig. 26.--Plot of increment velocity--90°--subject 2

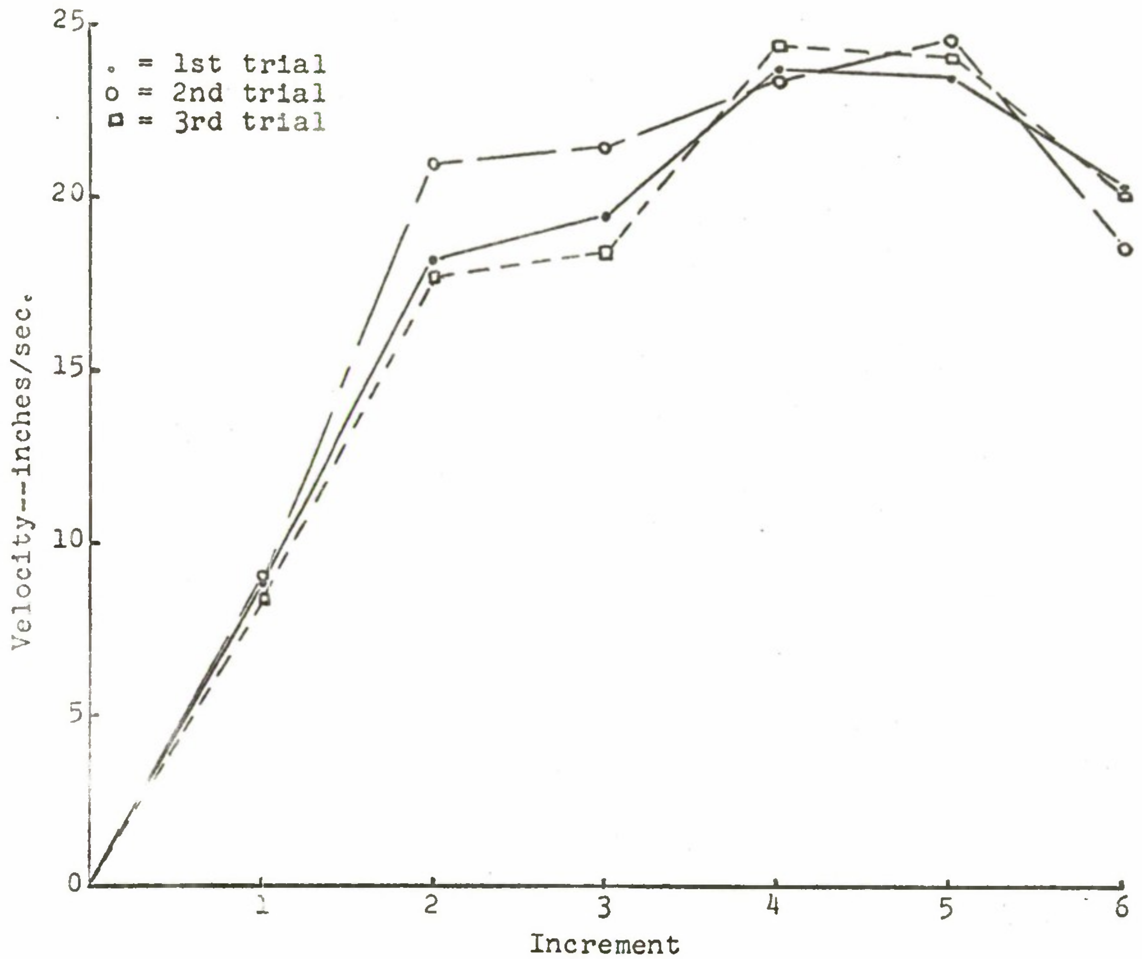


Fig. 27.--Plot of increment velocity--90°--subject 3

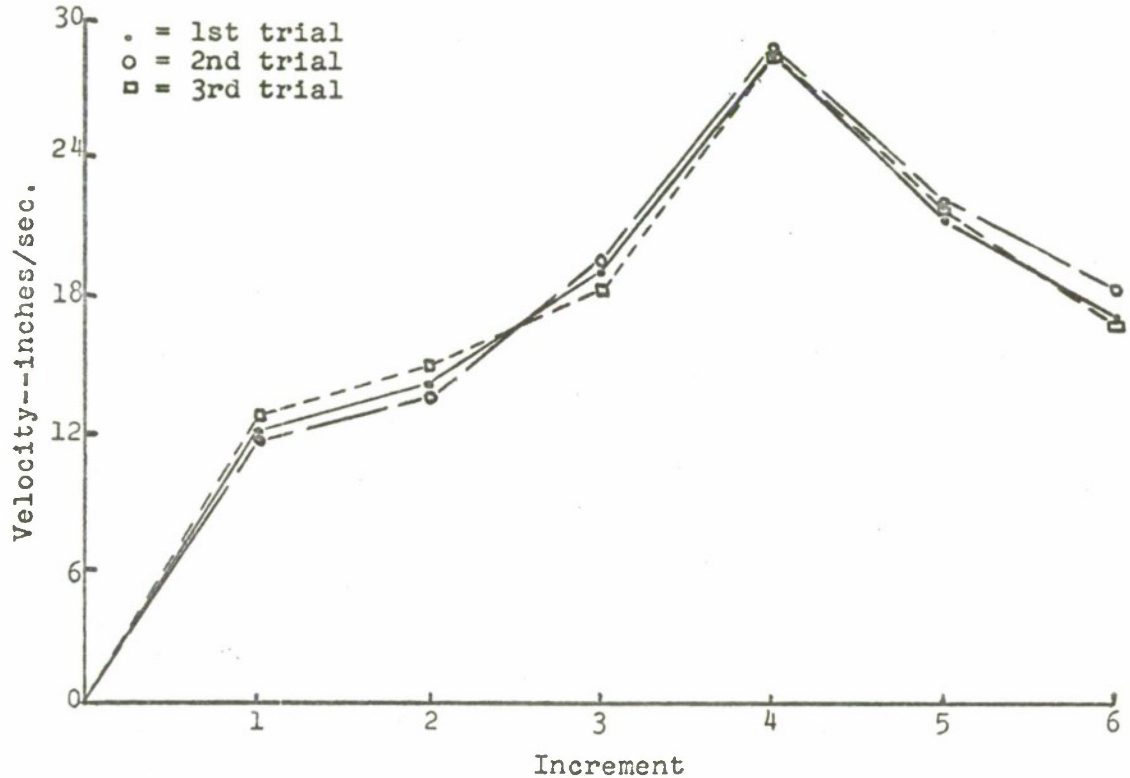


Fig. 28.--Plot of increment velocity--135°--subject 1

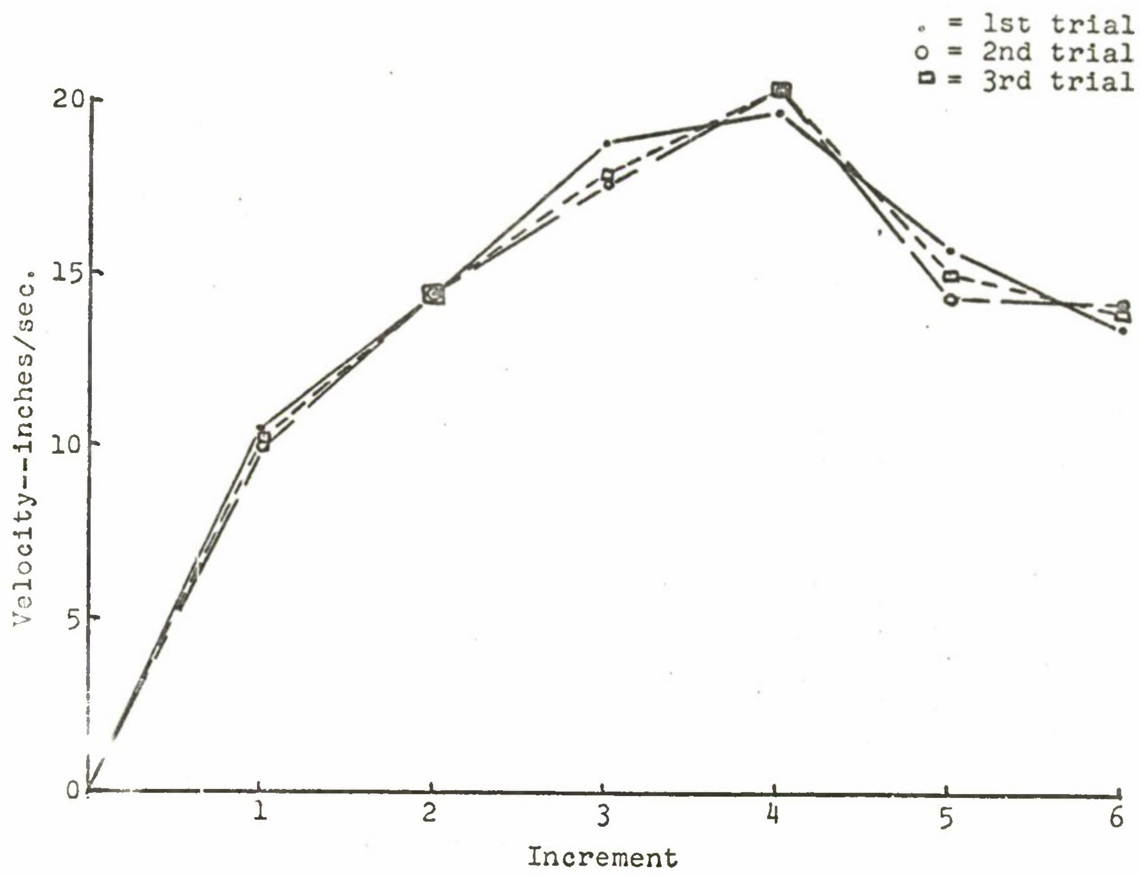


Fig. 29.--Plot of increment average velocity--135°--subject 2

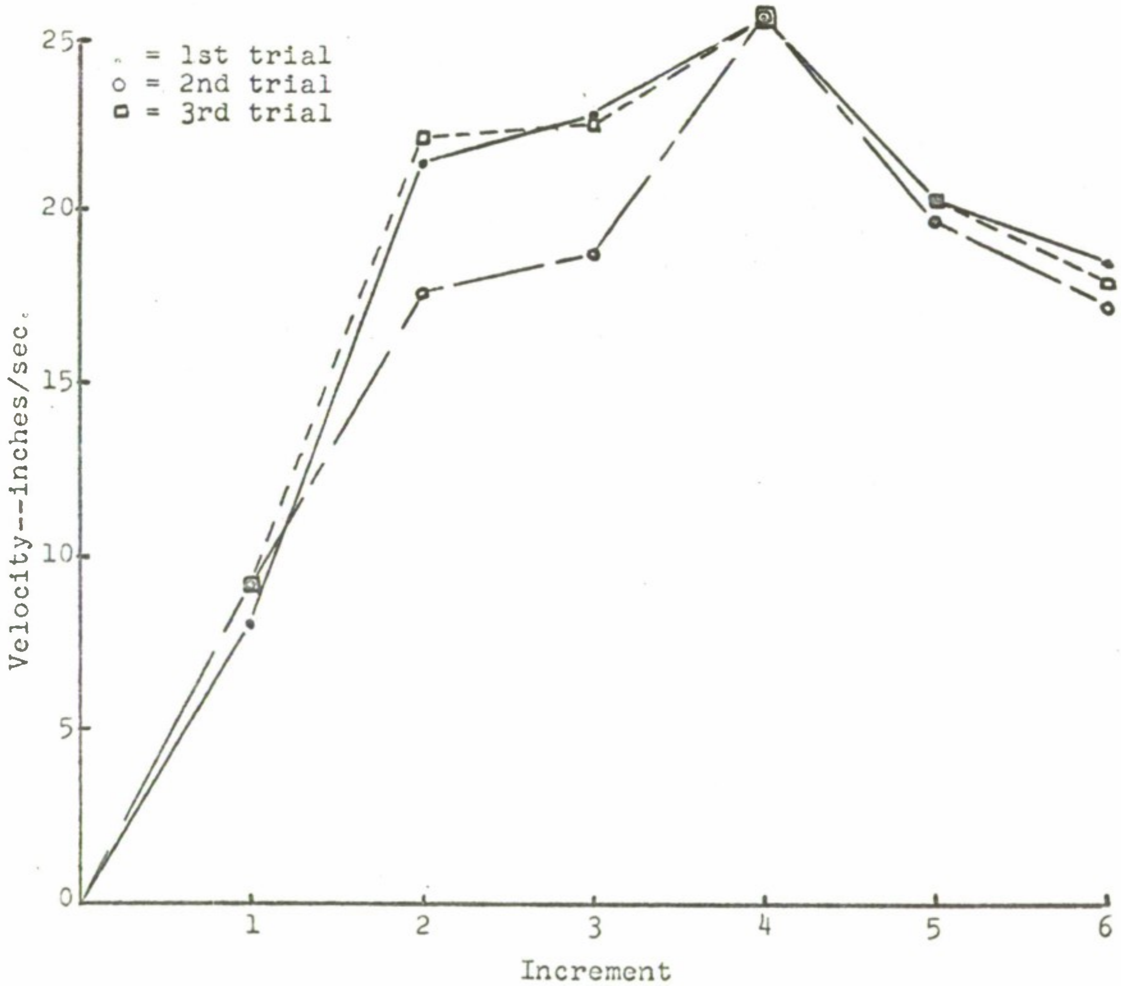


Fig. 30.--Plot of increment average velocity--135°--subject 3

compensate for the fast start to end up on the beat of the metronome. It should be noted that the average velocity is slightly higher than the 90 degree direction and much higher than the 0 and 45 degree directions. Figures 31, 32, 33, and 34 were included to show the combined averaged increment velocity for the 0, 45, 90, and 135 degree directions respectively. The averaged value includes the three trials for each subject.

Average total move velocity

Table 7 is included to show the average velocity for each move, for each subject, and the combined average velocity for each move. It should be noted that subject 2 moved at a slower rate than subjects 1 and 3; this variation can only be attributed to subject error. The combined averages show that the 135 and 90 degree moves have a much higher velocity than the 0 and 45 degree moves. Figure 13 (page 53) shows a plot of average velocity over the plot of average distance traveled. The plots obtained are similar. Figure 35 shows a plot of the average velocity for each direction of movement. As the figure indicates, the average velocities for the 135 and 90 degree moves are very close, and both are much higher than the 0 and 45 degree moves. The 0 degree direction has the slowest velocity, being approximately 4 inches/second slower than the 45 degree direction.

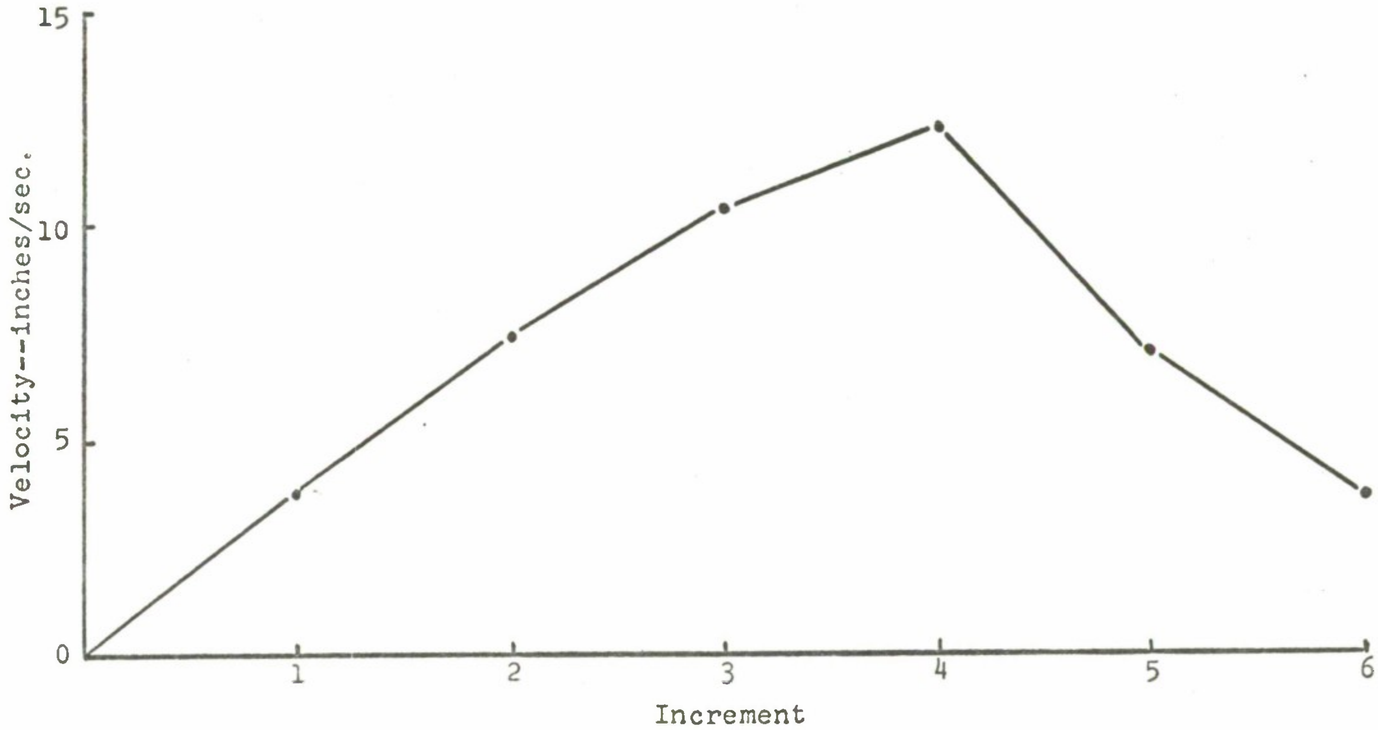


Fig. 31.--Plot of averaged increment velocity--0°

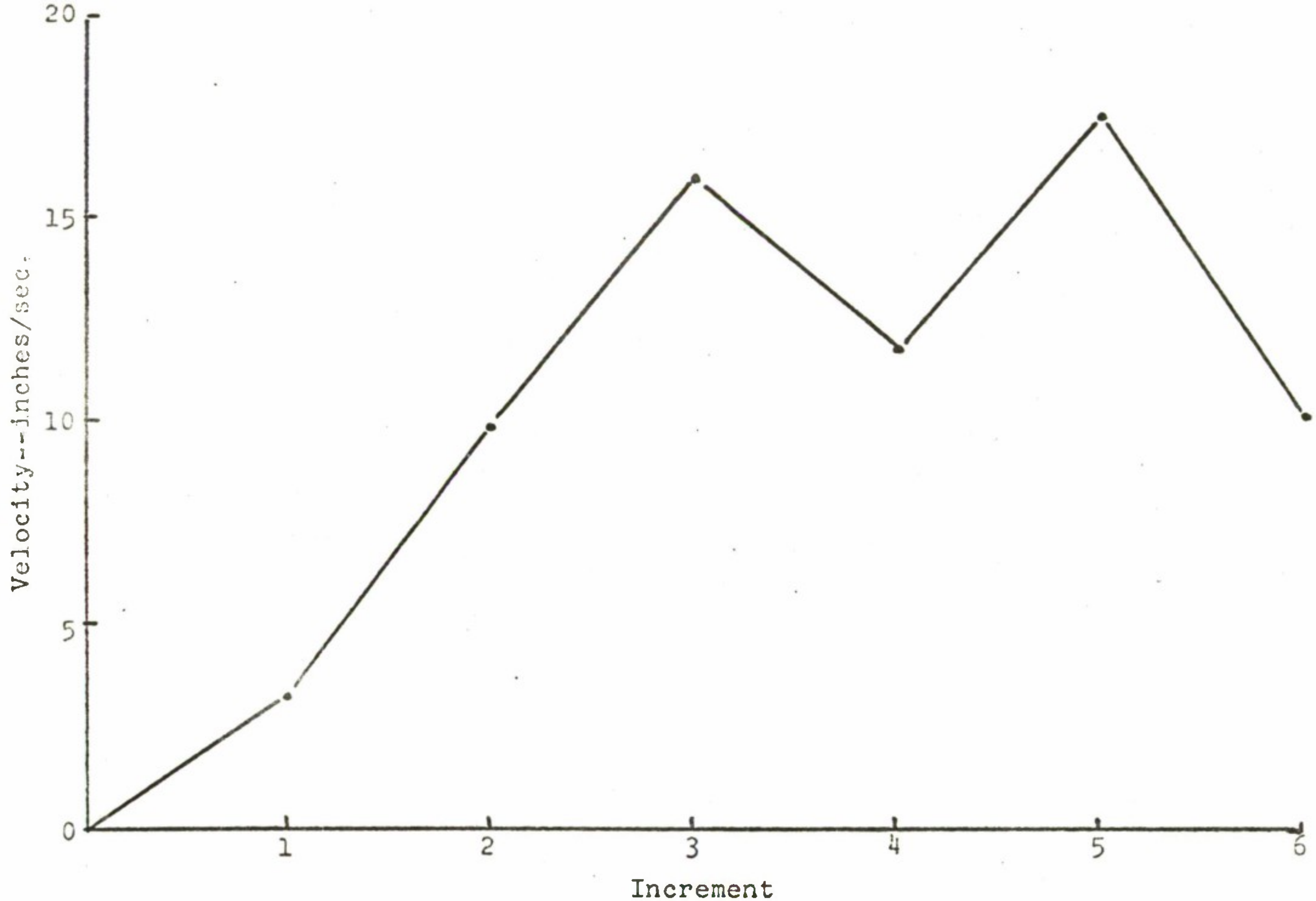


Fig. 32.--Plot of averaged increment velocity--45°

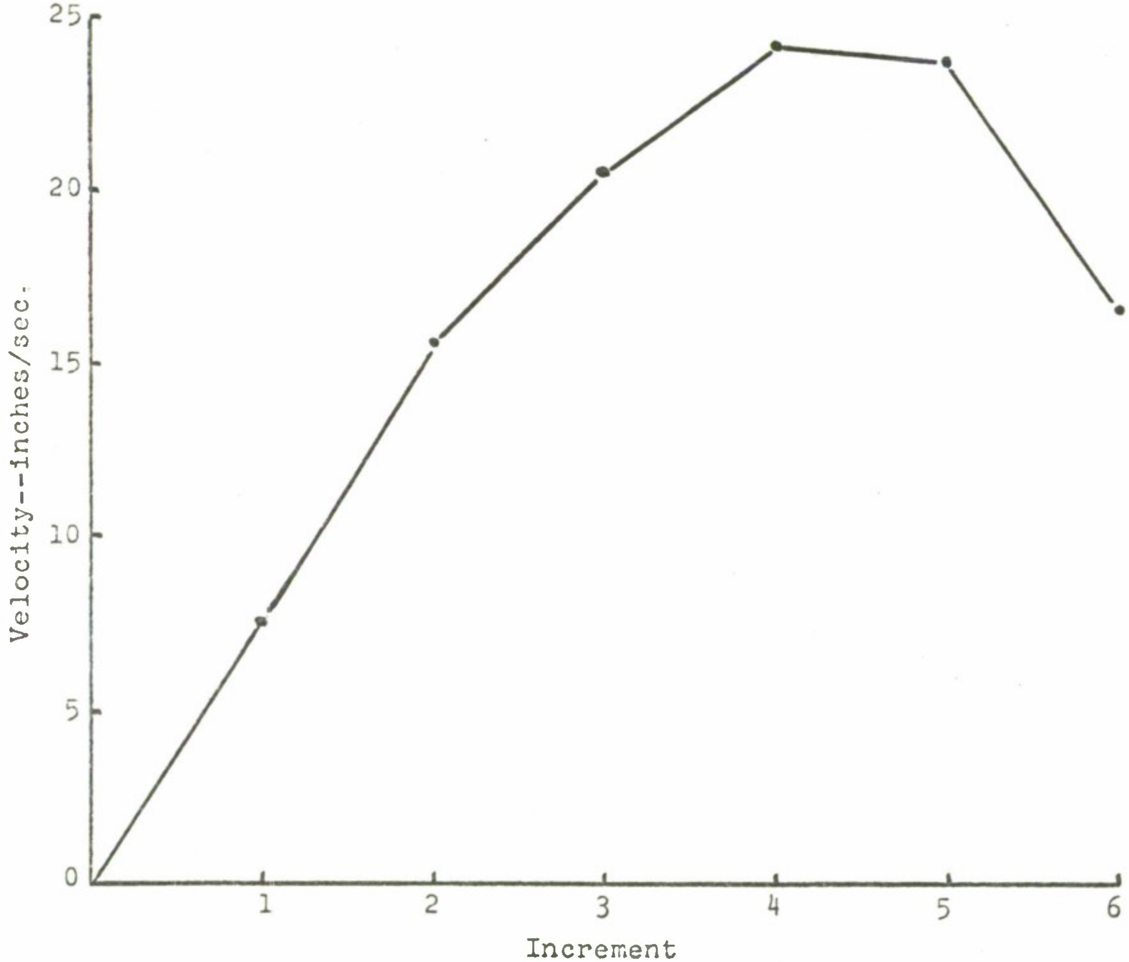


Fig. 33.--Plot of averaged increment velocity--90°

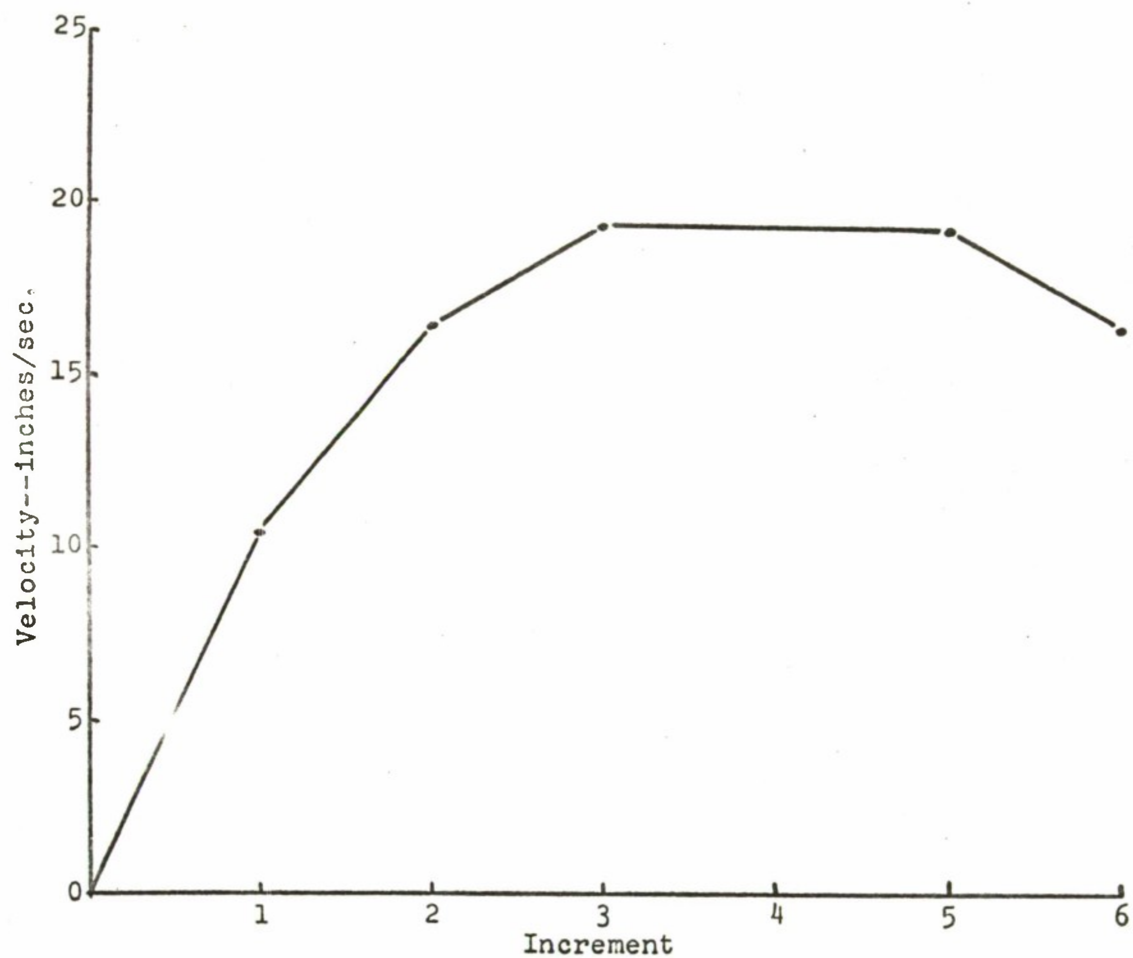


Fig. 34.--Plot of averaged increment velocity--135°

TABLE 7

TOTAL MOVE AVERAGE VELOCITY

Direction	Subject	Average Velocity	Standard Deviation
0°	1	7.06	.210
	2	5.81	.160
	3	6.85	.081
45°	1	10.27	.038
	2	8.65	.210
	3	11.31	.081
90°	1	17.56	.130
	2	13.58	.450
	3	17.54	.500
135°	1	17.69	.100
	2	14.48	.100
	3	17.90	.500

Direction	Combined Average	Standard Deviation
0°	6.57	.53
45°	10.08	1.10
90°	16.23	1.80
135°	16.69	1.54

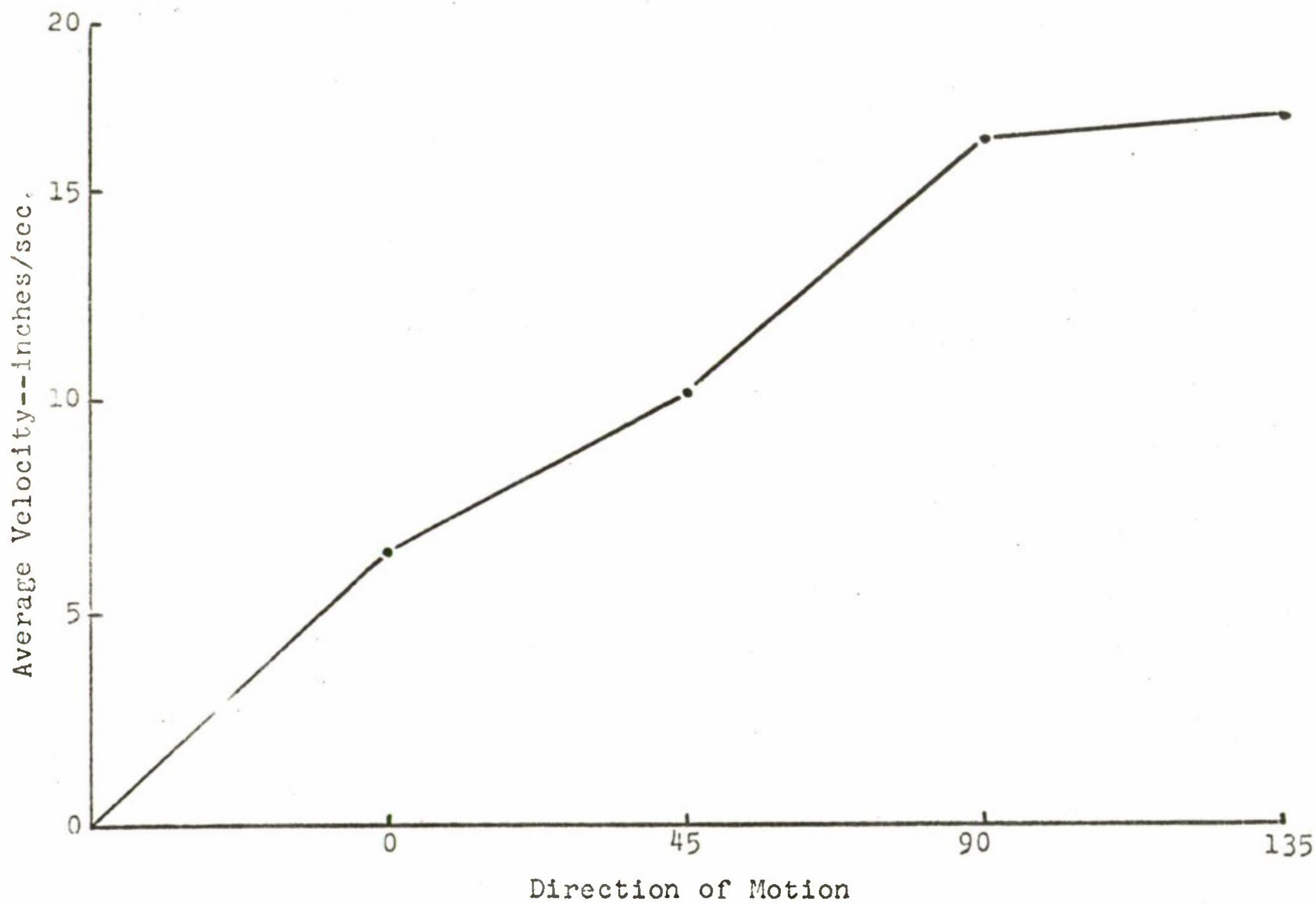


Fig. 35.--Plot of average velocity vs. direction of motion

Maximum velocity

Figure 36 is a plot of the average maximum velocity against the direction of motion. The plot shows that the maximum velocity increases with the angle of motion. The values for the velocity were obtained by taking the maximum value for each subject, for each direction, and averaging.

Hand Velocity

The velocity of the hand center of gravity was calculated, and this value was compared to the total arm center of gravity. To determine the relationship, if any, between the two velocities, the velocity of the hand center of gravity was divided by the arm center of gravity velocity. Table 8 was included to show these results. The comparisons show that the ratio of the velocity of the hand center of gravity to the total arm center of gravity is almost constant between subjects for each individual move, but the ratio is definitely not constant for all directions. Figure 37 was included to show the plot of the ratio versus the direction of motion. The value used for the ratio is obtained by averaging the data shown in Table 8.

The interpretation of the results presented in this chapter and their implications are presented in Chapter V.

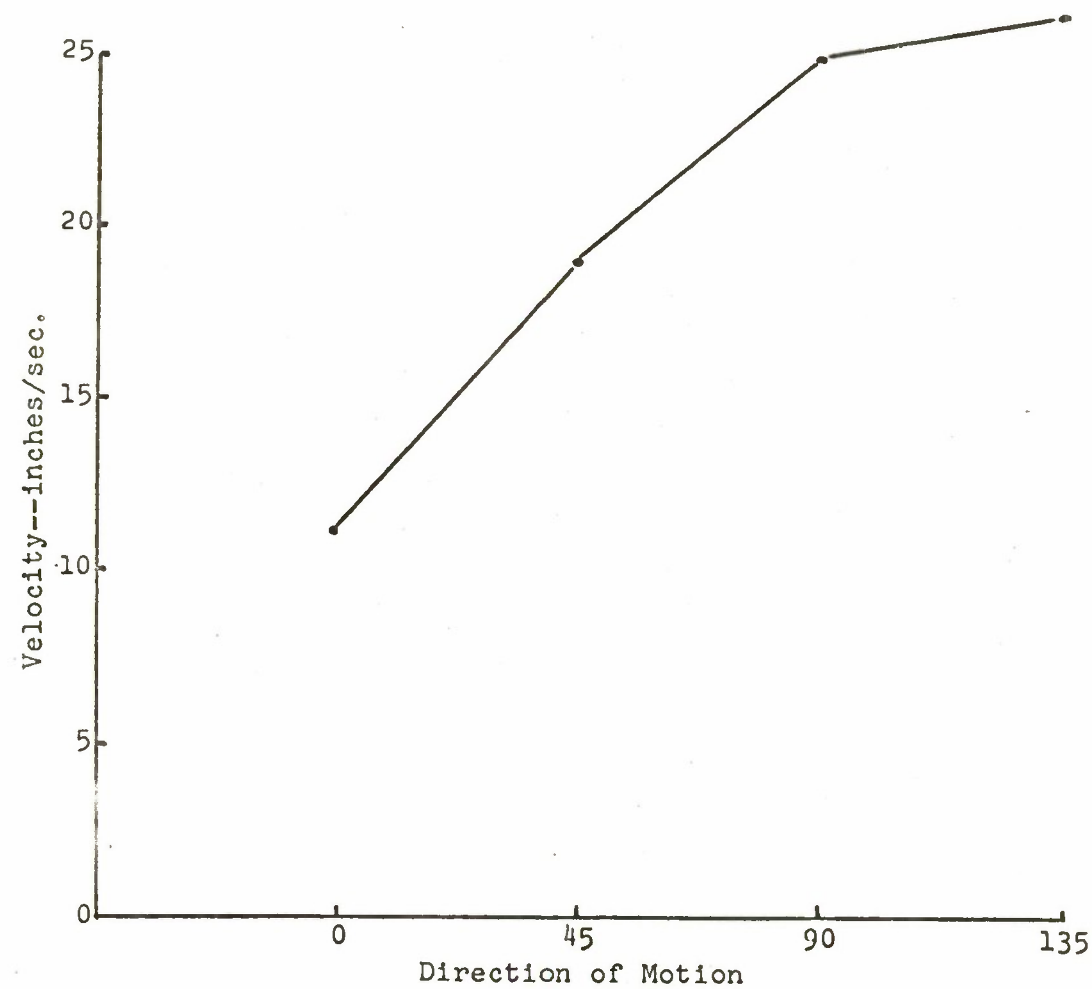


Fig. 36.--Plot of maximum velocity for each direction of motion

TABLE 8

COMPARISON BETWEEN AVERAGE VELOCITIES OF HAND CENTER OF GRAVITY AND ARM CENTER OF GRAVITY

Direction	Subject	Ratio
0°	1	2.6
	2	2.5
	3	2.4
45°	1	1.9
	2	1.9
	3	1.8
90°	1	1.3
	2	1.3
	3	1.3
135°	1	1.2
	2	1.3
	3	1.2

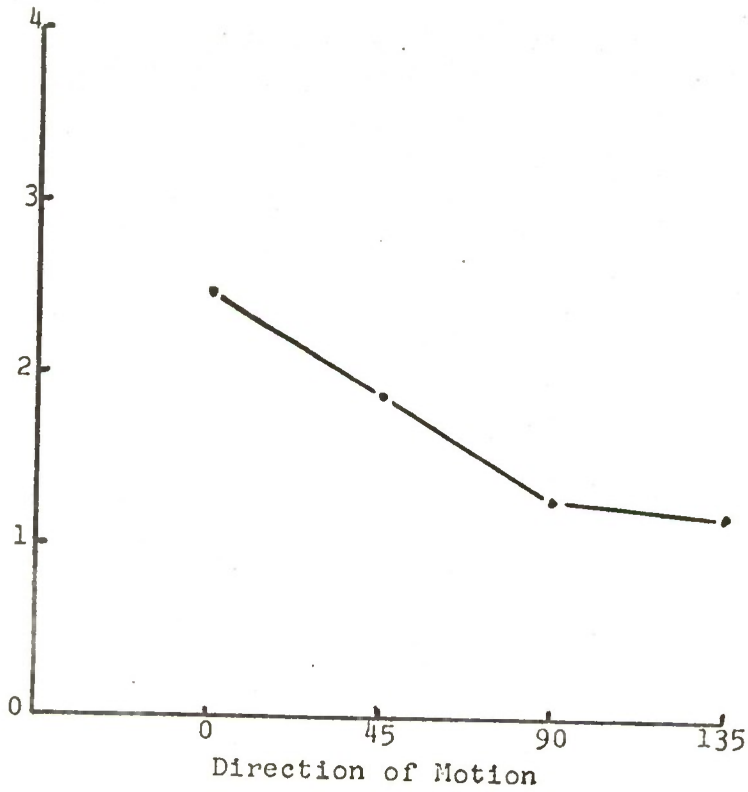


Fig. 37.--Ratio--velocity of center of gravity of hand/velocity of center of gravity of total arm.

CHAPTER V

CONCLUSIONS

In presenting the conclusions, any comparisons that can be made to previously reported related studies are made. In making these comparisons it must be kept in mind that this study is unique; thus direct comparisons with similar studies are impossible. The primary purpose of this study was to examine the distance, path and velocity characteristics of the arm center of gravity during certain arm movements that simulate work movements used by the seated worker. The conclusions that can be made within the limitations of this study are presented below.

Distance Moved

Figure 12 (page 50) shows the distance moved by the arm center of gravity for each subject during each direction of move. It was suspected that moves which required a greater extension of the arm would cause the arm center of gravity to travel a longer distance. As the angle of direction increases from 0 degrees to 135 degrees, a greater extension of the arm is required. Figure 12 shows that the distance moved by the arm center

of gravity increases as the angle of direction increases. Therefore, the results of this experiment support the speculation that greater extensions of the arm cause the arm center of gravity to travel a greater distance. Figure 12 also shows that the distance traveled by the arm center of gravity of each subject was extremely close for all subjects. While this study does not contain enough subjects to conclude that the distance traveled by the arm center of gravity approaches a constant for each direction, it does imply that this is a possibility.

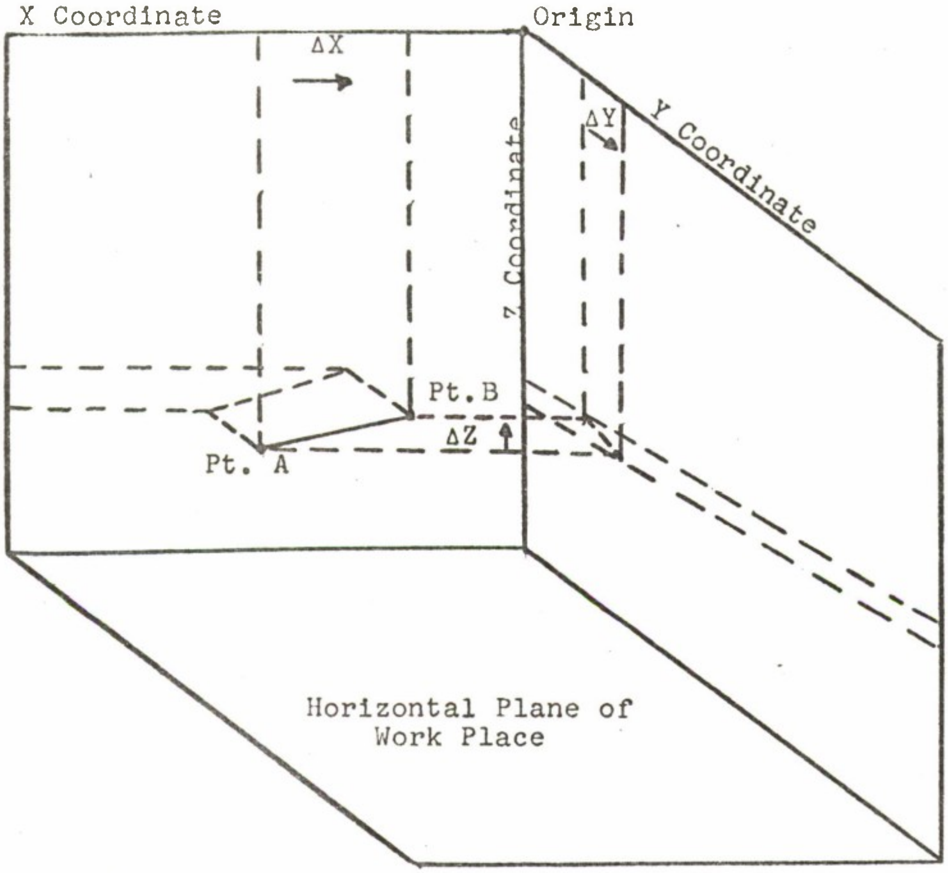
Figure 13 (page 53) shows the symmetrical plot of the distance traveled. The interesting result obtained from this plot was the fact that the area containing the minimum distance traveled is within the area composing the optimal work area as reported by studies on the optimal work area of the seated operator. While no definite conclusions can be drawn from this result, it does show that the arm center of gravity moves shorter distances in the optimal work area. This implies that a criterion other than time could possibly be used to define optimal work areas. Since work is defined as force times distance, the results also imply that less work is done when moving in the 0 to 45 degree range than in the other directions. The results of this study will not allow this to be made as a definite conclusion, but the implication certainly exists.

Path of Motion

The path traveled by the arm center of gravity was similar for each subject in each direction. The results were as expected and enable general conclusions to be drawn for each direction.

Figures 38, 39, 40, and 41 were included to show how the X, Y, Z coordinates change in the 0, 45, 90, and 135 degree directions respectively. In the 0 degree direction the X coordinate of the arm center of gravity decreased approximately 3 to 3-1/2 inches. As Figure 38 indicates, a decrease in the X coordinate means that it is moving toward the origin along the X coordinate during the move. The Y coordinate increased approximately 2 inches during the 0 degree direction. As Figure 38 indicates, an increase in the Y coordinate means it is moving away from the origin along the Y coordinate. The Z coordinate decreased approximately .6 inches. As Figure 38 indicates, a decrease in the Z coordinate means it is moving toward the origin along the Z coordinate. It was expected that the Z coordinate change would be small for the 0 degree direction, and this was verified.

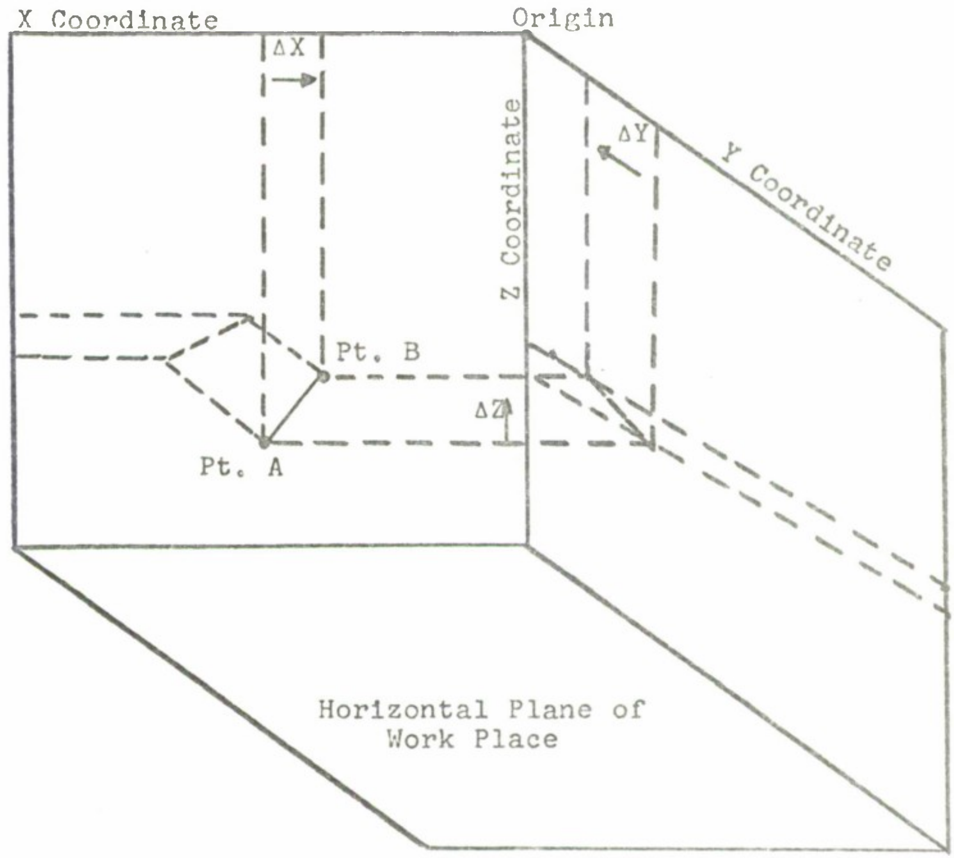
In the same manner as described above, Figure 39 shows the change in coordinates for the 45 degree move. The X coordinate decreased approximately 2 inches, the Y coordinate decreased approximately 4 inches, and the Z coordinate decreased approximately 1.5 inches.



Pt. A = Starting Point
Pt. B = Ending Point
ΔX = Change in X Coordinate = 3-3.5 inches
ΔY = Change in Y Coordinate = 2.0 inches
ΔZ = Change in Z Coordinate = 0.6 inches
Arrow (⟶) = Direction of Change

Fig. 38*.--0° Coordinate Change

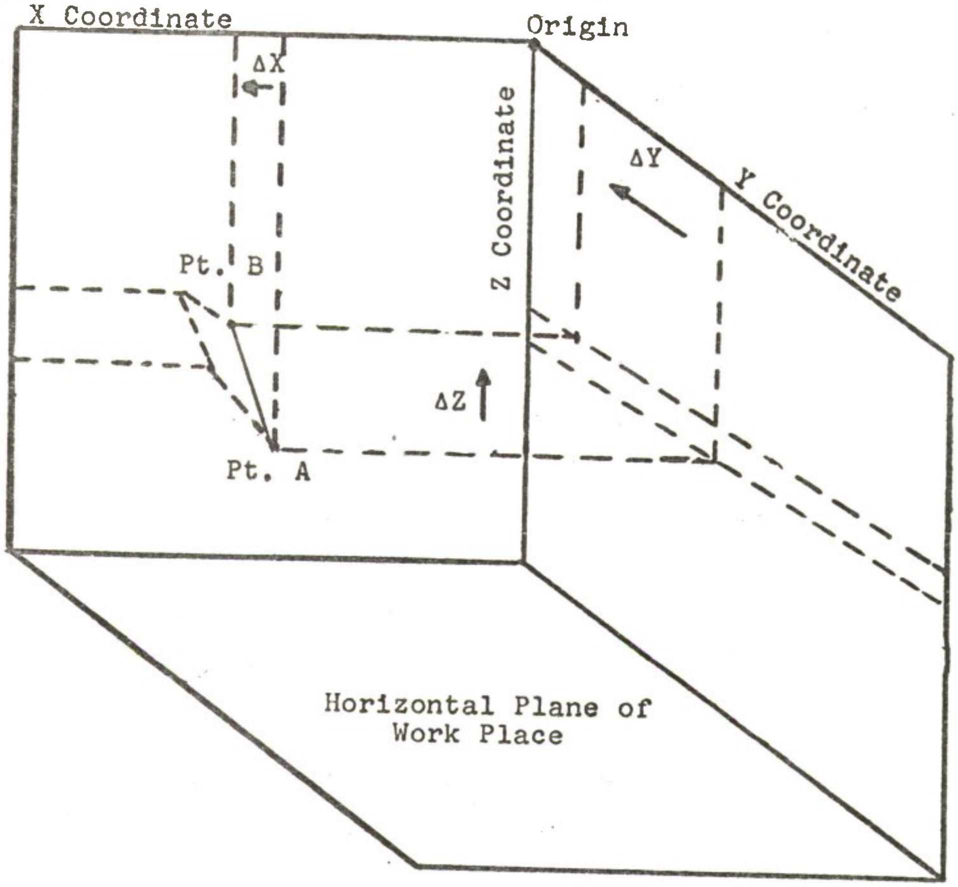
*Not drawn to scale.



Pt. A = Starting Point
Pt. B = Ending Point
ΔX = Change in X Coordinate = 2 inches
ΔY = Change in Y Coordinate = 4 inches
ΔZ = Change in Z Coordinate = 1.5 inches
Arrow (⟶) = Direction of Change

Fig. 39*.--45° Coordinate Change

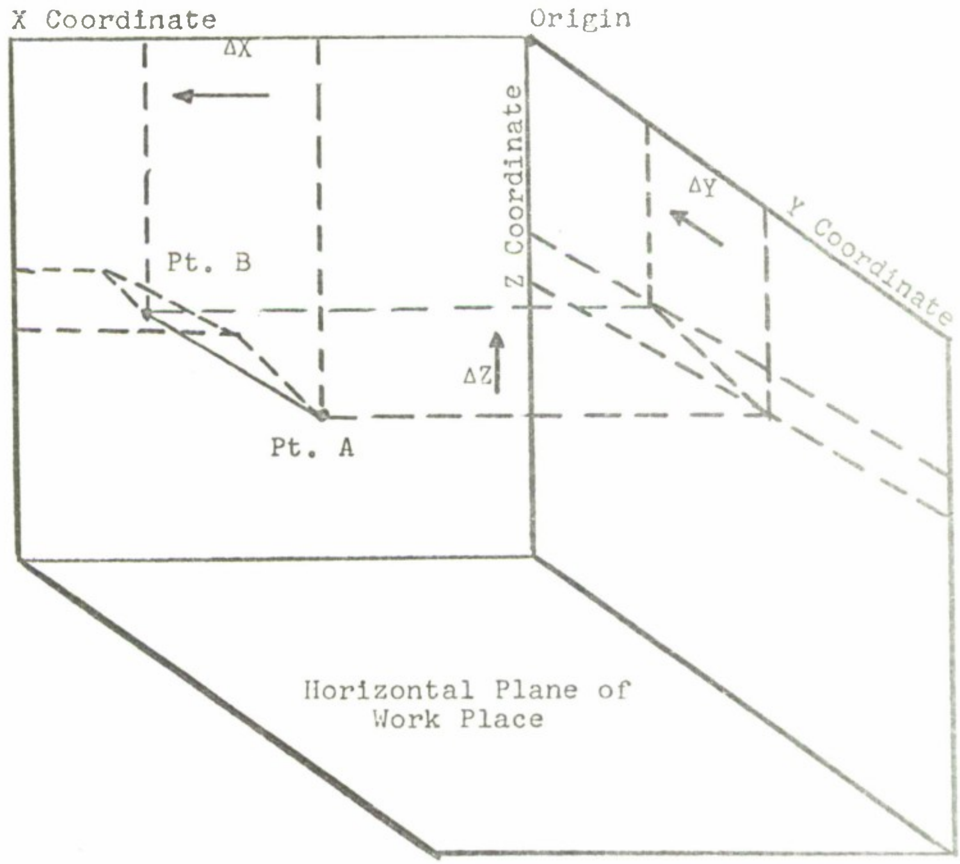
*Not drawn to scale.



Pt. A = Starting Point
Pt. B = Ending Point
ΔX = X Coordinate Change = +1 inches
ΔY = Y Coordinate Change = -8 inches
ΔZ = Z Coordinate Change = -2.2 inches
Arrow (⟶) = Direction of Change

Fig. 40*.--90° Coordinate Change

*Not drawn to scale.



Pt. A = Starting Point
Pt. B = Ending Point
ΔX = X Coordinate Change = +5.8 inches
ΔY = Y Coordinate Change = -7.8 inches
ΔZ = Z Coordinate Change = -2.4 inches
Arrow (⟶) = Direction of Change

Fig. 41*.--135° Coordinate Change

*Not drawn to scale.

Figure 40 (page 98) shows the change in coordinates for the 90 degree direction. The X coordinate increased approximately 1 inch, the Y coordinate decreased approximately 8 inches, and the Z coordinate decreased approximately 2.2 inches. Figure 41 (page 99) shows the change in coordinates for the 135 degree direction. The X coordinate increased approximately 5.8 inches, the Y coordinate decreased approximately 7.8 inches, and the Z coordinate decreased approximately 2.4 inches.

Average Increment Velocity

The increment velocity data yielded similar results for each subject and allowed general conclusions to be made about the behavior of the velocity of the arm center of gravity during the various moves. The behavior of the velocity will be described in terms of percent time of the total move.

The 0 degree direction yields a smooth increment velocity curve which reaches a maximum during the 51% to 71% time interval at a velocity of 12.2 inches per second and then decreases during the remainder of the move to an ending velocity of 3.8 inches per second. (Reference Figure 31, page 83.) The 45 degree direction yields a velocity curve which has a smooth increase for the first 54% of the move, then a decrease in velocity occurs during the 54% to 67% time interval. The velocity increases

again during the 67% to 80% interval and then decreases during the remainder of the move. (Reference Figure 32, page 84.) The decrease in velocity during the 54% to 67% interval is constant between subjects and is possibly due to the functional characteristics of the arm.

The 90 degree move yields a smooth velocity curve which reaches a maximum during the 58% to 70% time interval. There is very little decrease in velocity during the 70% to 83% interval; however, the velocity decreases rapidly during the remainder of the move. (Reference Figure 33, page 85.) The 135 degree direction yields a smooth velocity curve which reaches a maximum during the 58% to 71% time interval. The velocity then decreases during the remainder of the move. (Reference Figure 34, page 86.)

Average Velocity

The average velocity of the arm center of gravity for a move increased with the increase of the angle of direction. Figure 35, page 88, shows a plot of average velocity of the arm center of gravity against direction of move. The results of this experiment seem to indicate that as the angle of direction of motion increases, the average velocity of the arm center of gravity increases. This result is to be expected. A metronome was used and it held the time practically constant for all moves. Since

the distance moved by the arm center of gravity increased with an increase in the angle of direction, and velocity equals distance ÷ time, it follows that the velocity will increase with an increase in distance traveled. The results show that the 135 and 90 degree directions have a much larger average velocity than the 0 and 45 degree angles.

Maximum Velocity

The results of this experiment show that the maximum velocity attained during the various movements follows the same trend as the average velocity. (Reference Figure 36, page 90.) The maximum velocity attained increases as the angle of direction increases.

Hand Velocity

The velocity of the hand center of gravity was compared to the velocity of the arm to determine if any constant relationship existed. (Reference Table 8, page 91.) It was suspected that the velocity of the hand center of gravity divided by the velocity of the arm center of gravity might yield a relationship that would be constant for all moves. The results of this experiment do not verify this speculation. However, the results did yield almost a constant ratio for each individual move. This result suggests the possibility of a nonlinear relationship between the ratios for each move. This study

does not contain enough subjects to verify this possibility, but as Figure 37 (page 92) shows, this nonlinear relationship could exist.

Additional Conclusions

The results of the distance traveled by the center of gravity of the arm in the various directions considered in this experiment indicate that the optimal work area could possibly be defined in terms of the distance traveled by the center of gravity of the arm. This experiment shows that the minimum distance traveled by the arm center of gravity occurs at approximately 20 to 30 degrees and then increases as the angle increases. In general, the distance traveled in the area of 0 to 60 degrees is quite small as compared to the 60 to 180 degree area. Since the area of 0 to 60 degrees contains the optimal work area found by Goodwin [17], Wyatt [18], and Schmidtke and Stier [16], the results indicate that the center of gravity of the arm travels a smaller distance in the reported optimal work area.

An extension of the study of the center of gravity of the arm seems to the author to be justifiable. Some particular questions that arise from this study that need to be investigated are listed below. These questions are offered for possible research areas, as the author feels the answers to the questions will be a positive

contribution to the knowledge of the center of gravity of the arm and its effect on industrial tasks.

1. Are the conclusions reported here applicable to three-dimensional tasks? The task investigated in this experiment was limited to the horizontal plane.

2. How would curved line motion affect the results? This experiment limited all moves to straight line motion.

3. What effect would external weight carried by the hand have on the results of this experiment?

4. Additional research is required to determine the functional relationship, if such a relationship exists, between the ratio of the velocity of the center of gravity of the hand and the velocity of the center of gravity of the total arm for each direction of motion.

5. Is there less work done in the moves where the arm center of gravity travels a smaller distance? A calorimetric experiment could be combined with this experiment to verify or deny this implication.

6. Can the optimal work area of a seated worker be defined in terms of the distance traveled by the arm center of gravity? Particular interest should be applied to this subject combined with question 5. If the optimal work area can be defined by the distance traveled by the arm center of gravity and the answer to question 6 is

positive, then the optimal work area will have the additional quality of demanding the least physiological cost from the worker.

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APPENDIX

A. Location of Arm Segments' Centers of Gravity

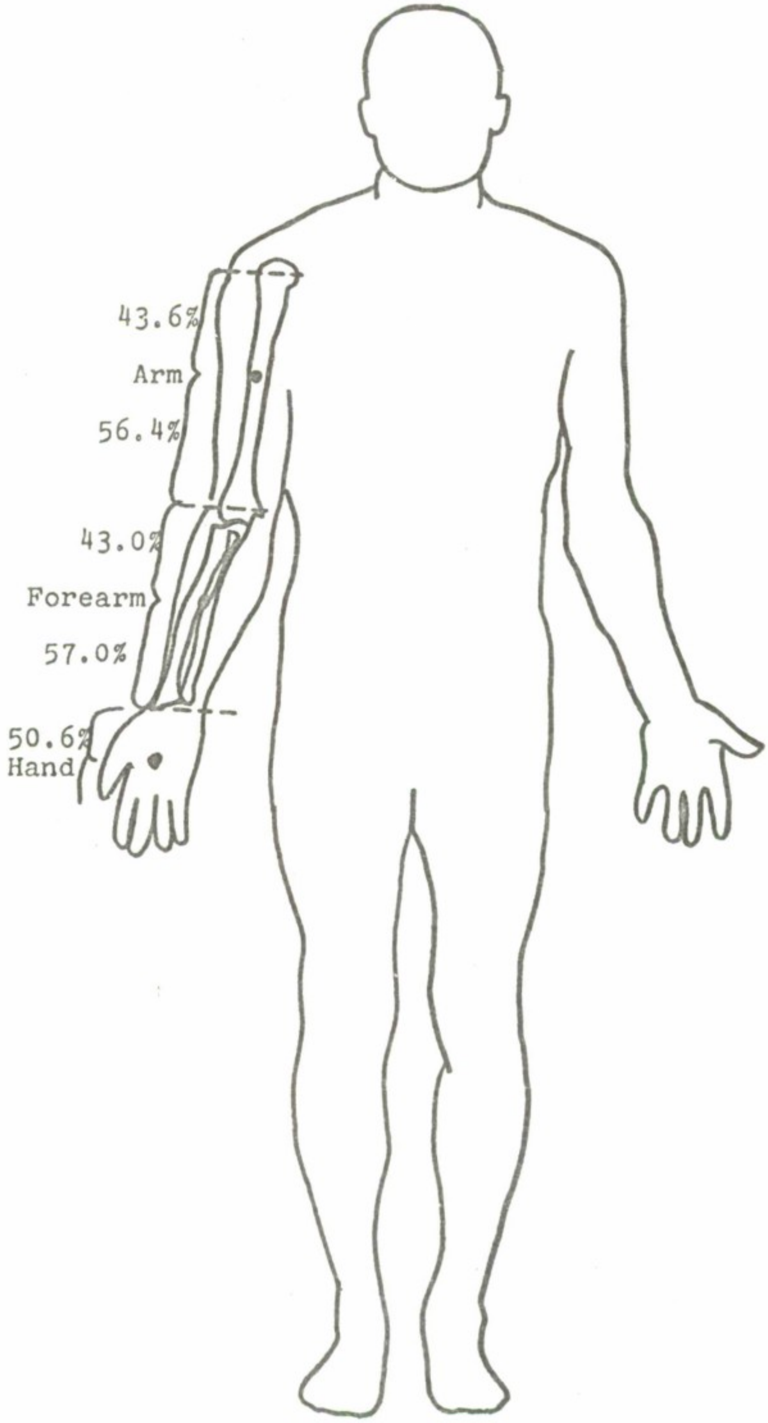
B. Surface Landmarks Associated with the Joint Centers of the Arm

C. Segment Weight As a Percentage of Total Weight

D. Location of the Arm Segments' Centers of Gravity

E. Computer Program

APPENDIX A



Location of Arm Segments' Centers of Gravity

APPENDIX B

SURFACE LANDMARKS ASSOCIATED WITH THE JOINT CENTERS OF THE ARM*

Glenohumeral--Mid-region of palpable bony mass of hand and tuberosities of humerus.

Elbow-- Mid-point of line between: (1) lowest palpable point of medial epicondyle of humerus, and (2) a point 8 mm. above radiohumeral junction.

Wrist-- (Palmar surface)--Distal crease at palmaris longus tendon; or mid-point of line between radial styloid and center of pisiform bone. (Dorsal surface)--Palpable groove between lunate and capitate bones, on a line with metacarpal III.

*Data taken from reference 5; reference 5 contains data for all body joint centers.

APPENDIX C

TABLE 9

SEGMENT WEIGHT AS A PERCENTAGE OF TOTAL WEIGHT*

Segment	% of Total Body Weights
Upper Arm	2.7
Forearm	1.6
Hand	0.6

*Data taken from reference 5; reference 5 contains data for all body segments.

APPENDIX D

LOCATION OF THE ARM SEGMENTS' CENTERS OF GRAVITY*

Upper Arm--In medial head of triceps, adjacent to radial groove; 5 mm. proximal to distal end of deltoid insertion.

Forearm-- 11 mm. proximal to most distal part of pronator teres insertion; 9 mm. anterior to interosseus membrane.

Hand-- On axis of metacarpal III, usually 2 mm. deep to volar skin surface; 2 mm. proximal to proximal transverse palmar skin crease, in angle between proximal transverse and radial longitudinal crease.

*Data taken from reference 5; reference 5 contains data for all body segments.

APPENDIX E

COMPUTER PROGRAM

```
C   C  PROGRAM  FOR  MASTERS  THESIS
       DIMENSION  R(3,7),   A(3,7),  O(3,7),  X(3,7),  Y(3,7),   Z(3,7)
       DIMENSION  XR(7),  YR(7),  ZR(7)
       DIMENSION ED(6),  EN(6),   AV(6) ,  HA(6)
       READ 10,  WHAND,  WFORE,  WUPP
    10 FORMAT  (3F8.4)
       READ 20,((R(I,J),J=1,7),I=1,3)
    20 FORMAT(7F8.4)
       READ30, ((A(I,J), J=1,7), I=1,3)
    30 FORMAT(7F6.2)
       READ40, ((O(I,J), J=1,7),I=1,3)
    40 FORMAT(7F6.2)
       READ  180,  (EN(J),  J=1,6)
   180 FORMAT(6F8.4)
       READ  190,  TOLTM
   190 FORMAT(1F8.4)
       DO 50 I=1,3
       DO 50 J=1,7
    50 A(I,J)= A(I,J) * 0.01745
       DO 60 I=1,3
       DO 60 J=1,7
    60 O(I,J) = O(I,J) * 0.01745
       DO 70 I=1,3
       DO70J=1,7
       X(I,J) = R(I,J) * COSF(A(I,J)) * SINF(O(I,J))
       Y(I,J)= R(I,J)*COSF(A(I,J))*COSF(O(I,J))
       Z(I,J)=R(I,J)*SINF(A(I,J))
       PUNCH 80, X(I.J) ,  Y(I,J) , Z(I,J)
    80 FORMAT(29H1ST7=HAND  2ND7=FORE  3RD7=UP, 3F8.4)
    70 CONTINUE
```

```
      DO90 J=1,7
      XR(J)=(WHAND*X(1,J)+WFORE*X(2,J)+WUPP*X(3,J))/(WHAND+WFORE+WUPP)
      YR(J)=(WHAND*Y(1,J)+WFORE*Y(2,J)+WUPP*Y(3,J))/(WHAND+WFORE+WUPP)
      ZR(J)=(WHAND*Z(1,J)+WFORE*Z(2,J)+WUPP*Z(3,J))/(WHAND+WFORE+WUPP)
      PUNCH100, XR(J),  YR(J),   ZR(J)
  100 FORMAT(4X, 3F8.4)
   90 CONTINUE
      DO 110  J=1,6
      FAC1=(XR(J=1)-XR(J))**2
      FAC2=(YR(J+1)-YR(J))**2
      FAC3=(ZR(J+1)-ZR(J))**2
      ED(J)=SQRTF(FAC1+FAC2+FAC3)
      PUNCH 120,  ED(J)
  120 FORMAT(4X, 20HINCREMENT DISTANCE  , 1F10,6)
  110 CONTINUE
      TOLDS=0.
      DO 130 J=1,6
  130 TOLDS = TOLDS + ED(J)
      PUNCH 140,  TOLDS
  140 FORMAT(4X,32HTOTAL DISTANCE MOVED BY C OF G =,1F10.6)
      DO 150  J=1,6
  150 AV(J)=ED(J)/(EN(J)/100.)
      PUNCH  160, (AV(J),J=1,6)
  160 FORMAT(4X,28HAVERAGE INCREMENT VELOCITY= ,1F10.6)
      TMAV=TOLDS/(TOLTM/100.)
      PUNCH 170,TMAV
  170 FORMAT(4X,30HTOTAL MOVE AVERAGE VELOCITY = ,1F10.6)
      DO 200I=1,1
      DO 200 J=1,6
      FACH1=(X(I,J+1)-X(I,J))**2
      FACH2=(Y(I,J+1)-Y(I,J))**2
      FACH3=(Z(I,J+1)-Z(I,J))**2
      HA(J)= SQRTF(FACH1+FACH2+FACH3)
      PUNCH 210, HA(J)
```

```
210 FORMAT(4X,14HHAND INC DIS =,1F10.6)
200 CONTINUE
    TODH=0.
    DO 220 J=1,6
220 TODH=TODH+HA(J)
    PUNCH230,TODH
230 FORMAT(4X,9HHAND DIS=,1F10.6)
    AVH= TODH/(TOLTM/100.)
    COMP=AVH/TMAV
    PUNCH240, COMP
240 FORMAT(4X,5HCOMP=,1F10.6)
    STOP
    END
```